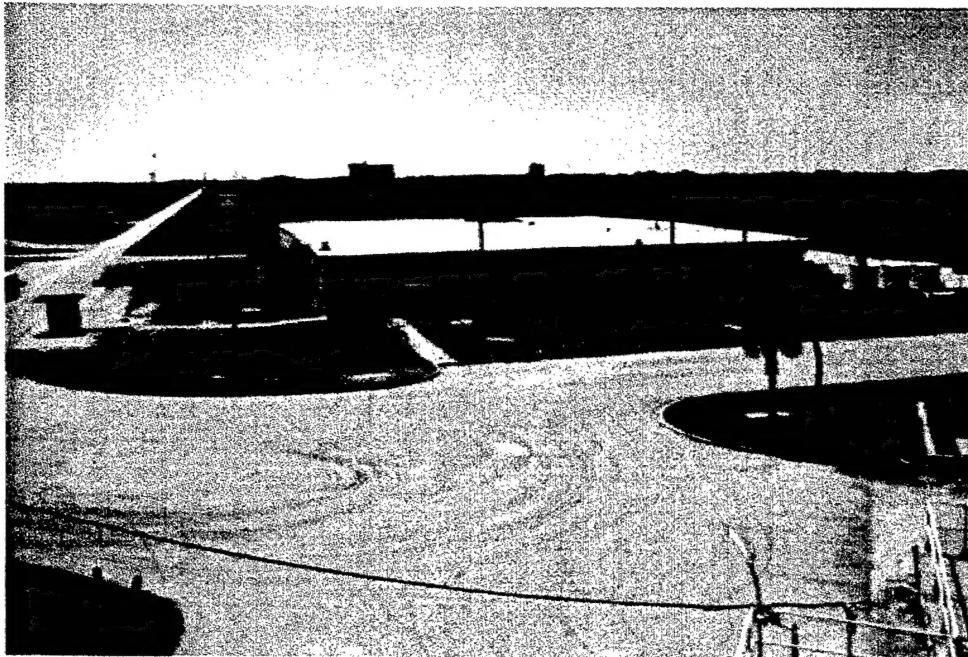


# **Chemical Oxidation of a DNAPL Source Zone at Launch Complex 34 in Cape Canaveral Air Station**

## **Draft Final Technology Evaluation Report**



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Prepared for

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**Dense, Nonaqueous-Phase Liquid (DNAPL) Source  
Zone at Launch Complex 34 in Cape Canaveral Air  
Force Station**

**Chemical Oxidation**

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## **Executive Summary**

Dense, nonaqueous-phase liquid (DNAPL) contaminants are a challenge to characterize and remediate at many sites where such contaminants have entered the aquifer due to past use or disposal practices. Chlorinated solvents, comprised of chlorinated volatile organic compounds (CVOCs), such as trichloroethylene (TCE) and perchloroethylene (PCE), are common DNAPL contaminants at sites where operations, such as aircraft maintenance, dry cleaning, metal finishing, and electronics manufacturing have historically occurred. In the past, because of the difficulty in identifying the DNAPL source zone, most remediation efforts focused on controlling the migration of the dissolved CVOC plume. In recent years, many site owners have had success in locating DNAPL sources. DNAPL source remediation is beneficial because once the source has been significantly mitigated, the strength and duration of the resulting plume can potentially be lowered in the long term, and sometimes in the short term as well.

### **The Interagency DNAPL Consortium**

The Interagency DNAPL Consortium (IDC) was formally established in 1999 by the U.S. Department of Energy (DOE), U.S. Environmental Protection Agency (U.S. EPA), Department of Defense (DoD), and National Aeronautics and Space Administration as a vehicle for marshalling the resources required to test innovative technologies that promise technical and economic advantages in DNAPL remediation. The IDC is advised by a Technical Advisory Group comprised of experts drawn from academia, industry, and government. The IDC and other supporting organizations facilitate technology transfer to site owners/managers through dissemination of the demonstration plans and results, presentations at public forums, a website, and visitor days at the site.

### **Demonstration Site and Technology**

In 1998, after preliminary site characterization conducted by Westinghouse Savannah River Company indicated the presence of a sizable DNAPL source at Launch Complex 34 in Cape Canaveral, Florida, the IDC selected this site for demonstrating three DNAPL remediation technologies. The surficial aquifer at this site lies approximately between 5 to 45 ft bgs. This aquifer can be subdivided into three stratigraphic units — the Upper Sand Unit, the Middle Fine-Grained Unit, and the Lower Sand Unit. Although the Middle Fine-Grained Unit is a conspicuous hydraulic barrier, a Lower Clay Unit underlying the surficial aquifer is considered to be the aquitard that contains the DNAPL source. The Lower Clay Unit appears to be pervasive throughout the demonstration area, although it is only up to 3 ft thick. The hydraulic gradient in the surficial aquifer is relatively flat. The native aquifer contains relatively high levels of chloride and total dissolved solids (TDS).

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The source zone was divided into three test plots, 75 ft × 50 ft each in size, for testing three technologies — chemical oxidation, Six-Phase Heating™ (SPH™), and steam injection. About 15 ft of each plot was under the Engineering Service Building. Chemical oxidation and SPH™ were tested concurrently between September 1999 and April/June 2000 in the two outer plots, separated by about 80 ft. Steam injection will be tested in the middle plot, beginning June 2001. The IDC contracted MSE Technology Applications, Inc., to conduct the vendor selection and subcontracting for the three technologies, as well as for tracking the costs of the demonstration. IT Corporation was the vendor selected for implementing chemical oxidation (using potassium permanganate) at Launch Complex 34. Potassium permanganate was selected because it is a strong oxidant, is relatively easy to handle, commonly available and inexpensive, does not generate strong exothermic reactions in the aquifer, and persists long enough in the environment to enable efficient distribution in the aquifer.

## Performance Assessment

The IDC contracted Battelle in 1998 to plan and conduct the technical and economic performance assessment of the three technologies. The EPA Superfund Innovative Technology Evaluation (SITE) Program and its contractor Tetra Tech EM, Inc., provided Quality Assurance (QA) oversight and field support for the performance assessment. Before the chemical oxidation field application, Battelle prepared a Quality Assurance Project Plan (QAPP) or test plan that was reviewed by all the project stakeholders. This report describes the results of the performance assessment of the chemical oxidation technology. The objectives of the performance assessment were:

- Estimating the TCE/DNAPL mass removal
- Evaluating changes in aquifer quality
- Evaluating the fate of the TCE/DNAPL removed from the Oxidation Plot
- Verifying chemical oxidation operating requirements and costs.

Estimating the TCE/DNAPL mass removal due to the chemical oxidation application was the primary objective of the demonstration in terms of resources expended for planning, data gathering, and interpretation; the other three were secondary, but important, objectives.

In February 1999, Battelle conducted the preliminary characterization of the DNAPL source region on the north side of the Engineering Service Building (ESB). This characterization provided preliminary DNAPL mass estimates and aquifer data to support the vendor's design of the technology application. It also provided data on the spatial variability of the TCE/DNAPL that supported the design of a more detailed characterization of each test plot before the demonstration. In June 1999, a detailed pre-demonstration characterization of the Oxidation Plot was conducted to initiate the performance assessment of the chemical oxidation technology. From September 1999 to April 2000, when the chemical oxidation field application was conducted, Battelle collected subsurface data to monitor the progress of the demonstration; the vendor collected additional data to aid in the operation of the technology. In May 2000, the postdemonstration assessment of the Oxidation Plot was conducted.

## TCE/DNAPL Mass Removal

Detailed soil sampling was used as the main tool for determining TCE/DNAPL mass removal. The spatial distribution data from the preliminary characterization were used to determine a statistically significant number and location of soil samples required to obtain good coverage of the Oxidation Plot. A systematic unaligned sampling scheme

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was used to conduct pre- and postdemonstration soil coring at 12 locations in a  $4 \times 3$  grid in the test plot. Continuous soil samples were collected at every 2-ft vertical interval in each core, resulting in nearly 300 soil samples in the Oxidation Plot during each event. A vertical section (approximately 200 g of wet soil) from each 2-ft interval was collected and extracted with methanol in the field; the methanol extract was sent to a certified laboratory for analysis. In this manner, the entire soil column was analyzed from ground surface to aquitard, at each coring location. Predemonstration evaluation of this extraction method with Launch Complex 34 soil showed between 72 and 86% TCE recovery.

The TCE concentrations (mg/kg of dry soil) obtained by this method were considered "total TCE." The portion of the total TCE that exceeded a threshold concentration of 300 mg/kg was considered "DNAPL." This threshold was determined as the maximum TCE concentration in the dissolved and adsorbed phases in the Launch Complex 34 soil; any TCE concentration exceeding this threshold would be DNAPL.

The results of the TCE/DNAPL mass removal evaluation by soil sampling show the following:

- Contouring or linear interpolation of TCE concentrations between sampled points indicated that there was 6,122 kg of total TCE in the Oxidation Plot before the demonstration; approximately 5,039 kg of this TCE mass was DNAPL. Approximately 82% of the total TCE mass and 84% of the DNAPL mass was removed from the plot due to the chemical oxidation application. This predicted removal is less than the 90% DNAPL removal target proposed at the beginning of the demonstration, but is still a significant achievement for the technology.
- A statistical evaluation of the pre- and postdemonstration TCE concentrations confirmed these results. Kriging, a geostatistical tool that takes the spatial variability of the TCE distribution into account, indicated that between 5,459 and 10,040 kg of total TCE was present in the test plot before the demonstration. Kriging indicated that between 62 and 84% of the total TCE was removed from the test plot by the technology application. A pairwise comparison of the pre- and postdemonstration TCE/DNAPL data confirmed that significant TCE/DNAPL removal was achieved in most portions of the plot. These statistics are significant at the 80% confidence level specified before the demonstration.
- The highest TCE/DNAPL mass removal was obtained in the Upper Sand Unit, followed by the Lower Sand Unit. The Middle Fine-Grained Unit showed the least removal. This shows that the oxidant distribution was most effective in the coarser soils. The level of TCE/DNAPL removal was not as high under the building as outside it, indicating that these regions could not be efficiently accessed from outside the building. The general radius of influence of the potassium permanganate appeared to be less than 15 ft around the injection points, although preferential flowpaths sometimes transferred the oxidant to more distant locations.

## **Changes in Aquifer Quality**

Application of the chemical oxidation technology caused the following short-term changes in the treated aquifer:

- Dissolved TCE levels declined sharply in several monitoring wells in the Oxidation Plot, with some wells showing postdemonstration concentrations of less than 5  $\mu\text{g/L}$ , the federal drinking water standard. Achievement of the State of Florida groundwater target cleanup level of 3  $\mu\text{g/L}$  could not be determined because excessive permanganate in several of the postdemonstration ground-

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water samples caused analytical interference and required dilution. In some wells within the Oxidation Plot, TCE levels declined, but stayed above 5 µg/L. In one of the shallow wells, TCE levels rose through the demonstration, indicating that local heterogeneities (limited oxidant distribution) or redistribution of groundwater flow due to partial DNAPL removal may have affected dissolved TCE levels. *Cis*-1,2 DCE levels in all monitoring wells declined to below 70 µg/L. Vinyl chloride levels in some wells declined to less than 1 µg/L, the State of Florida target; in some wells, higher TCE levels elevated the detection limits of vinyl chloride. This indicated that chemical oxidation considerably improved groundwater quality in the short term. In the long term, some rebound may occur; on the other hand, excess permanganate in some parts of the plot may continue to diffuse into difficult pores and remove more DNAPL mass. In any case, DNAPL mass removal is expected to lead to eventual and earlier disappearance of the plume over the long term. There is also the possibility that even in the medium term, as normal groundwater flow is reestablished, a weakened plume may be generated and the resulting CVOC levels may be amenable to natural attenuation.

- Groundwater pH and dissolved oxygen levels remained stable, but oxidation-reduction potential (ORP), chloride, alkalinity, and TDS levels rose. TDS levels were above the secondary drinking water standard of 500 mg/L both before and after the demonstration, classifying the aquifer as brackish. Dissolved manganese levels rose above the 50 µg/L secondary drinking water standard; the dissolved manganese is expected to be mostly Mn<sup>7+</sup>; a reduced form of manganese (Mn<sup>2+</sup>) may also be generated as the aquifer reverts to reducing conditions.
- Biological oxidation demand and total organic carbon (TOC) levels in the groundwater generally increased. TOC in soil remained relatively constant through the demonstration. These parameters were expected to decrease following oxidation. Dissolved iron levels remained relatively constant, and sulfate levels increased. The anomalous behavior of these parameters indicates that the oxidant-contaminant-aquifer reactions are more complex and may result in a wider variety of byproducts.
- The groundwater levels of three trace metals—chromium, nickel, and thallium—showed a short-term increase above State of Florida targets. The presence of these metals in the industrial-grade permanganate used as the oxidant is expected to have contributed to the elevated levels of these metals. Another possible source for some of the chromium could be the stainless steel monitoring wells in the plot; although stainless steel is resistant to the oxidant, high levels of chloride can cause corrosion. The elevated levels of these trace metals are expected to subside over time.
- Slug tests conducted in the Oxidation Plot before and after the demonstration did not indicate any noticeable changes in the hydraulic conductivity of the aquifer; any manganese dioxide accumulation in the aquifer did not appear to have affected its hydraulic properties.

### ***Fate of TCE/DNAPL Removed***

The TCE/DNAPL removed from the plot could have taken several pathways, including destruction by oxidation, migration to surrounding aquifer, or migration to vadose zone/atmosphere.

- The sharp rise in chloride levels in all three stratigraphic units is the strongest indicator that destruction by oxidation contributed significantly to TCE/DNAPL

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mass removal in the plot. The rise in chloride levels was conspicuous even above the relatively high native chloride in the groundwater and despite dilution from the hydrant water used to make up the permanganate solution.

- The large increase in aquifer alkalinity, a sign of carbon dioxide generation, is a strong indicator of oxidation reactions in the aquifer, although not of TCE alone. Native organic matter may also account for some of the oxidant consumption and carbon dioxide generation.
- Some DNAPL movement occurred in the saturated zone after the start of the chemical oxidation and SPH™ demonstrations. However, because the DNAPL appeared in monitoring wells between the two test plots, it is difficult to attribute the cause of the DNAPL movement to one of the two technologies. If the strong hydraulic gradient created by the oxidant injection caused DNAPL to migrate, the DNAPL would have to have been present in mobile, and not residual, form. A limited number of additional soil cores collected around the Oxidation Plot did not show any signs of DNAPL accumulation. Monitoring of the vadose zone and surface atmosphere did not indicate any TCE/DNAPL migration in the upward direction, as could have happened had exothermic reactions taken place in the aquifer. No monitoring was conducted below the Lower Clay Unit because of NASA's concerns over breaching the aquitard.

### ***Verifying Operating Requirements***

The vendor injected a total of 842,985 gal of permanganate solution (or 66,956 kg of solid potassium permanganate) in three injection cycles over an 8-month period. In the first injection cycle, the vendor injected the oxidant (1 to 2% solution of potassium permanganate) through 11 more-or-less equally spaced locations. At each location, the vendor advanced a specially designed injection tip in 2-ft intervals, using a Geoprobe®. The amount of permanganate injected at each location and depth was based on prior knowledge of the TCE/DNAPL distribution.

The injection pressure, flowrate, and period of injection were used to control the radius of influence of the permanganate around the injection point. The vendor estimates that 10 to 12 ft or less radius of influence was achieved at some injection points. However, local heterogeneities, DNAPL content, and native organic matter content limited oxidant distribution at some points, as indicated by the varying flow-rates achieved. For example, whereas one injection point would permit 2 to 3 gpm of flow, another point only one horizontal foot away would permit less than 0.1 gpm of flow. Both groundwater and soil samples indicated (visually and analytically) that oxidant distribution varied in different parts of the plot. The portion of the aquifer underneath the building also appeared to have received insufficient oxidant; the plot extended 15 ft inside the building, whereas all injections were conducted outside.

Both the vendor and Battelle conducted additional monitoring in the periods between each injection cycle. During the second and third injection cycles, the vendor focused on only those portions of the plot that this interim monitoring showed had not received sufficient oxidant during the previous cycle.

Use of heavy equipment and handling of a strong oxidant were the primary hazards during the operation. The operators wore Level D protection at most times, except when a respirator had to be worn to spray any dust generated while handling the dry potassium permanganate oxidant. A solution consisting of vinegar and hydrogen peroxide was kept on site to neutralize any exposure to potassium permanganate solution due to spills or hose leaks. The permanganate delivery system was automated so that it would shut off if any excessive pressure (clogging) or loss of pressure (leaks) was experienced in the system.

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## **Economics**

The vendor incurred a total cost of approximately \$1 million for the field application of chemical oxidation process. This includes the design, procurement, mobilization/demobilization, oxidant injection, and process monitoring. The vendor estimates that approximately 15% of this cost was demonstration related. In addition, NASA incurred site preparation costs of \$2,800. No aboveground wastes were generated from the injections and waste disposal costs were minimal and were limited to nonhazardous solid waste disposal of materials generated during mobilization and operation.

A comparison of the cost of chemical oxidation treatment of the DNAPL source the size of the Oxidation Plot and an equivalent (2 gpm) pump-and-treat system for plume control over the next 30 years was conducted to evaluate the long-term economic impact of the technology. The chemical oxidation application cost was found to be less than the present value (PV) of a 30-year pump-and-treat application. This comparison assumes that natural attenuation would be sufficient to address any residual source. Also, in the absence of source treatment, the plume emanating from this relatively large DNAPL source may be expected to last much more than 30 years. Chemical oxidation and natural attenuation require none of the above-ground structures, recurring operational costs, and maintenance that pump-and-treat systems require. Anecdotal evidence indicates that, at many sites, pump-and-treat systems are operational only about 50% of the time. The impact of this downtime and the associated maintenance costs should also be considered. In general, the economics favor DNAPL source treatment, and chemical oxidation (noninjection mode) in particular, over a pump-and-treat system at this site.

Site characterization costs were not included in the cost comparison because a good design of a source treatment or plume control remedial action is assumed to require approximately the same degree of characterization. The site characterization conducted by Battelle in February 1999 is typical of the characterization effort that may be required for delineating a 75-ft x 50-ft DNAPL source; the cost of this effort was \$255,000, which included a work plan, 12 continuous soil cores to 45 ft bgs, installation of 36 monitoring wells, field sampling, laboratory analysis of samples, field parameter measurements, hydraulic testing, and data analysis and report.

## ***Summary of Conclusions and Recommendations***

As described above, the following conclusions were drawn from the chemical oxidation demonstration:

- Approximately 82% of the total TCE mass and 84% of the DNAPL mass in the source zone was removed by chemical oxidation.
- Much of this removal can be attributed to destruction of TCE by oxidation, as indicated by the chloride buildup in the plot. The sharp increase in carbon dioxide and, consequently, alkalinity levels in the groundwater, is another sign of considerable oxidation occurring in the aquifer.
- Dissolved TCE levels declined considerably in most parts of the test plot in the short term. The federal drinking water standard for TCE (5 µg/L) was met in several monitoring wells during postdemonstration monitoring. Achievement of the lower State of Florida standard (3 µg/L) could not be determined due to analytical interference from the permanganate. The *cis*-1,2 DCE and vinyl chloride levels in the many parts of the plot declined considerably as well.
- It is possible to achieve a relatively good distribution of permanganate oxidant in sandy soils. Distribution of oxidant is more difficult in finer-grained soils.

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A radius of influence of 10 to 12 ft around the injection point was achieved at several locations. However, at some locations, resistance to oxidant flow was considerable, and the radius of influence was much smaller. Local geologic heterogeneities and native organic matter content of the aquifer may limit oxidant distribution in some regions. These factors may have also limited the reach of the oxidant under the building, from the injection points located outside.

- Elevated levels of some trace metals, such as chromium, nickel, and thallium, may occur in the short term. The source of these trace metals is probably the industrial-grade permanganate used and possibly the stainless steel monitoring wells. Levels of dissolved manganese, a species subject to secondary drinking water standards, may be elevated in the short term as well. The concentrations of the trace metals and other dissolved species were found to mitigate quickly with distance from the treatment area. Elevated levels of even potassium ion, a relatively conservative species, subsided by the time the groundwater moved about 80 to 100 ft from the plot. This indicates that permanganate oxidation, even in an injection-only mode, can be applied at locations that are relatively close to receptors or property boundaries.
- Some DNAPL appeared in monitoring wells located between the two test plots, where chemical oxidation and SPH™ technologies were being applied concurrently. It is difficult to attribute the DNAPL migration to one of the two technologies. The strong hydraulic gradient generated by the oxidant injection is unlikely to cause DNAPL migration, unless some DNAPL is already present in mobile form. When permanganate is used as the oxidant, there are no strong exothermic reactions involved and the potential for migration of DNAPL to the vadose zone or atmosphere is minimal.
- The cost of the chemical oxidation application was approximately \$1 million, including the design, oxidant purchase, equipment procurement and installation, operation, and limited monitoring costs. The vendor estimates that approximately 15% of these costs were demonstration related. A comparison of the DNAPL source treatment with chemical oxidation cost with the life cycle cost of an equivalent pump-and-treat system at the site showed that the chemical oxidation treatment was more economical in the long term.

Based on the lessons learned during the demonstration, the following recommendations can be made for future applications:

- It is important to delineate the boundaries of the DNAPL source zone as well as resources will allow. A treatment such as oxidation also requires knowledge of the distribution of the DNAPL in the source region. The chemical oxidation treatment can be better targeted and injections can be arranged suitably to mitigate any potential for DNAPL migration. A combination of monitoring well clusters with discrete screened intervals and strategically located continuous soil cores are a good way of delineating the source, in preparation for remedial design and treatment.
- Pumping of the aquifer prior to oxidant injection should be considered to recover any mobile DNAPL; this will result in additional cost for aboveground treatment.
- If the DNAPL source boundaries can be identified with a fair degree of confidence, an injection-only scheme should be applied in such a way that the oxidant is first injected around the perimeter of the source, and then applied progressively to inner regions. This will minimize the potential for DNAPL migration. Alternatively, extraction wells can be used for better hydraulic control, but this will involve additional costs for aboveground treatment and reinjection/disposal of extracted fluids.

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- For the portion of a DNAPL source that is under a building, the oxidant can be more effectively distributed by locating injection points inside the building. This may create administrative difficulties if the building is in use, but will lead to more effective source removal. Alternatively, angled injection points or injection-extraction schemes with injection at one end of the building and extraction at another end could be considered.
- The native hydraulic gradient at this site is relatively flat, but the high injection pressures that were used here and that were required to achieve a reasonable radius of influence indicate that the native groundwater flow is not likely to play a significant role in oxidant distribution on the localized scale of most DNAPL zones. For schemes that rely on lower injection pressures, injection points would have to be much more closely spaced and injections would have to start much further upgradient to take advantage of the natural gradient and obtain good coverage of the plot.
- One way of lowering oxidant injection pressures, if desirable at a site, may be to inject lower concentrations of oxidant for a longer period of time. This will mitigate the potential for elevated trace metal levels in the groundwater during the application, but may lead to higher operational costs.
- Sodium permanganate, which is commercially available as a concentrated solution, may be used to ease the difficulties associated with the handling of a solid oxidant (potassium permanganate).
- Additional research is required to elucidate the geochemistry of the oxidant-aquifer-contaminant interactions, particularly the effects of the oxidant on native organic matter and the effects of excessive chloride generation on underground structures, such as monitoring wells or buildings. Additional research also is required to evaluate any rebound of dissolved CVOC concentrations in the long term and to evaluate the survival and regrowth of microbial populations in the plot. These factors are important for natural attenuation of any residual contamination following chemical oxidation treatment.

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## Contents

Executive Summary .....	v
Appendices.....	xv
Figures .....	xvi
Tables.....	xix
Acronyms and Abbreviations .....	xx
1. Introduction.....	1
1.1 Project Background .....	1
1.1.1 The Interagency DNAPL Consortium .....	1
1.1.2 Performance Assessment.....	2
1.1.3 The SITE Program .....	3
1.2 The DNAPL Problem.....	3
1.3 The Chemical Oxidation Technology .....	4
1.4 The Demonstration Site .....	4
1.5 Technology Evaluation Report Structure .....	6
2. Site Characterization.....	8
2.1 Hydrogeology of the Site .....	8
2.2 Surface Water Bodies at the Site .....	10
2.3 TCE/DNAPL Contamination in the Oxidation Plot and Vicinity.....	10
2.4 Aquifer Quality/Geochemistry .....	17
2.5 Aquifer Microbiology.....	18
3. Technology Operation.....	19
3.1 In Situ Chemical Oxidation Concept .....	19
3.2 Application of Chemical Oxidation at Launch Complex 34 .....	19
3.2.1 Chemical Oxidation Equipment and Setup at Launch Complex 34 .....	19
3.2.2 Chemical Oxidation Field Operation .....	21
3.3 Health and Safety Issues .....	26
4. Performance Assessment Methodology .....	27
4.1 Estimating the TCE/DNAPL Mass Removal .....	27
4.1.1 Contouring.....	30
4.1.2 Kriging .....	32
4.1.3 Pairwise Comparison .....	32
4.1.4 Interpreting the Results of the Three Mass Removal Estimation Methods.....	32
4.2 Evaluating Changes in Aquifer Quality .....	32
4.3 Evaluating the Fate of the TCE/DNAPL Mass Removed.....	33
4.4 Verifying Chemical Oxidation Operating Requirements and Costs .....	33

<b>5. Performance Assessment Results and Conclusions .....</b>	<b>34</b>
<b>5.1 TCE/DNAPL Mass Removal .....</b>	<b>34</b>
<b>5.1.1 Qualitative Evaluation of Changes in TCE/DNAPL Distribution.....</b>	<b>34</b>
<b>5.1.2 TCE/DNAPL Mass Removal Estimation by Contouring.....</b>	<b>38</b>
<b>5.1.3 TCE Mass Removal Estimation by Kriging .....</b>	<b>38</b>
<b>5.1.4 TCE/DNAPL Mass Removal Evaluation by Pairwise Comparison .....</b>	<b>43</b>
<b>5.1.5 TCE/DNAPL Mass Removal Summary.....</b>	<b>45</b>
<b>5.2 Changes in Aquifer Characteristics.....</b>	<b>45</b>
<b>5.2.1 Changes in CVOC Levels in Groundwater .....</b>	<b>47</b>
<b>5.2.2 Changes in Aquifer Geochemistry .....</b>	<b>47</b>
<b>5.2.3 Changes in the Hydraulic Properties of the Aquifer.....</b>	<b>52</b>
<b>5.2.4 Summary of Changes in Aquifer Quality.....</b>	<b>53</b>
<b>5.3 Fate of the TCE/DNAPL Mass Removed.....</b>	<b>53</b>
<b>5.3.1 DNAPL Destruction through Oxidation of TCE .....</b>	<b>53</b>
<b>5.3.2 Potential for DNAPL Migration from the Oxidation Plot .....</b>	<b>57</b>
<b>5.3.3 Summary Evaluation of the Fate of TCE/DNAPL .....</b>	<b>63</b>
<b>5.4 Operating Requirements and Cost.....</b>	<b>63</b>
<b>6. Quality Assurance .....</b>	<b>64</b>
<b>6.1 QA Measures .....</b>	<b>64</b>
<b>6.1.1 Representativeness .....</b>	<b>64</b>
<b>6.1.2 Completeness .....</b>	<b>65</b>
<b>6.1.3 Chain of Custody.....</b>	<b>65</b>
<b>6.2 Field QC Measures .....</b>	<b>65</b>
<b>6.2.1 Field QC for Soil Sampling .....</b>	<b>65</b>
<b>6.2.2 Field QC Checks for Groundwater Sampling .....</b>	<b>66</b>
<b>6.3 Laboratory QC Checks.....</b>	<b>67</b>
<b>6.3.1 Analytical QC Checks for Soil .....</b>	<b>67</b>
<b>6.3.2 Laboratory QC for Groundwater.....</b>	<b>67</b>
<b>6.3.3 Analytical Detection Limits .....</b>	<b>68</b>
<b>6.4 QA/QC Summary .....</b>	<b>68</b>
<b>7. Economic Analysis .....</b>	<b>69</b>
<b>7.1 Chemical Oxidation Treatment Costs .....</b>	<b>69</b>
<b>7.2 Site Preparation Costs .....</b>	<b>69</b>
<b>7.3 Site Characterization and Performance Assessment Costs .....</b>	<b>70</b>
<b>7.4 Present Value Analysis of Chemical Oxidation and Pump-and-Treat System Costs .....</b>	<b>70</b>
<b>8. Technology Applications Analysis.....</b>	<b>72</b>
<b>8.1 Objectives.....</b>	<b>72</b>
<b>8.1.1 Overall Protection of Human Health and the Environment.....</b>	<b>72</b>
<b>8.1.2 Compliance with ARARs .....</b>	<b>72</b>
<b>8.1.2.1 Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) .....</b>	<b>72</b>
<b>8.1.2.2 Resource Conservation and Recovery Act (RCRA).....</b>	<b>73</b>
<b>8.1.2.3 Clean Water Act (CWA).....</b>	<b>73</b>
<b>8.1.2.4 Safe Drinking Water Act (SDWA) .....</b>	<b>73</b>
<b>8.1.2.5 Clean Air Act (CAA) .....</b>	<b>74</b>
<b>8.1.2.6 Occupational Safety and Health Administration (OSHA) .....</b>	<b>74</b>
<b>8.1.3 Long-Term Effectiveness and Permanence.....</b>	<b>74</b>
<b>8.1.4 Reduction of Toxicity, Mobility, or Volume through Treatment.....</b>	<b>75</b>
<b>8.1.5 Short-Term Effectiveness.....</b>	<b>75</b>
<b>8.1.6 Implementability .....</b>	<b>75</b>

---

8.1.7	Cost .....	75
8.1.8	State Acceptance .....	75
8.1.9	Community Acceptance .....	76
8.2	Operability .....	76
8.3	Applicable Wastes .....	76
8.4	Key Features .....	76
8.5	Availability/Transportability .....	76
8.6	Materials Handling Requirements .....	76
8.7	Ranges of Suitable Site Characteristics .....	77
8.8	Limitations .....	77
9.	References .....	78

## Appendices

### Appendix A. Performance Assessment Methods

- A.1 Statistical Design and Data Analysis Methods
- A.3 Sample Collection and Extraction Methods
- A.3 List of Standard Sample Collection and Analytical Methods

### Appendix B. Hydrogeologic Measurements

### Appendix C. CVOC Measurements

- C.1 CVOC Measurements in Groundwater
- C.2 TCE Analysis of Additional Soil Cores outside the Oxidation Plot

### Appendix D. Inorganic and Other Aquifer Parameters

### Appendix E. Microbiological Assessment

### Appendix F. Surface Emissions Testing

- F.1 Surface Emission Test Methodology
- F.2 Surface Emission Test Results

### Appendix G. Quality Assurance/ Quality Control Information

### Appendix H. Economic Analysis Information

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## Figures

Figure 1-1.	Project Organization for the IDC Demonstration at Launch Complex 34 .....	2
Figure 1-2.	Formation of a DNAPL Source in an Aquifer .....	3
Figure 1-3.	In Situ Chemical Oxidation of a DNAPL Source Zone.....	4
Figure 1-4.	Demonstration Site Location.....	5
Figure 1-5.	Location Map of Launch Complex 34 Site at Cape Canaveral Air Station .....	6
Figure 1-6.	Looking Southward towards Launch Complex 34, the Engineering Service Building, and the Three Test Plots.....	7
Figure 2-1.	East-West Geologic Cross Section through the Three Test Plots.....	9
Figure 2-2.	North-South Geologic Cross Section through the Oxidation Plot.....	9
Figure 2-3.	Water-Level Map from June 1998.....	11
Figure 2-4.	Predemonstration Water Levels (as Elevations msl) in Shallow Wells at Launch Complex 34 .....	12
Figure 2-5.	Predemonstration Water Levels (as Elevations msl) in Intermediate Wells at Launch Complex 34 .....	13
Figure 2-6.	Predemonstration Water Levels (as Elevations msl) in Deep Wells at Launch Complex 34 .....	13
Figure 2-7.	Predemonstration Dissolved TCE Concentrations ( $\mu\text{g}/\text{L}$ ) in Shallow Wells at Launch Complex 34 .....	14
Figure 2-8.	Predemonstration Dissolved TCE Concentrations ( $\mu\text{g}/\text{L}$ ) in Intermediate Wells at Launch Complex 34 .....	14
Figure 2-9.	Predemonstration Dissolved TCE Concentrations ( $\mu\text{g}/\text{L}$ ) in Deep Wells at Launch Complex 34 .....	15
Figure 2-10.	Predemonstration TCE Concentrations (mg/kg) in the Upper Sand Unit Soil at Launch Complex 34.....	15
Figure 2-11.	Predemonstration TCE Concentrations (mg/kg) in the Middle Fine-Grained Unit Soil at Launch Complex 34.....	16
Figure 2-12.	Predemonstration TCE Concentrations (mg/kg) in the Lower Sand Unit Soil at Launch Complex 34.....	16
Figure 2-13.	Vertical Cross Section through Oxidation Plot Showing TCE Concentrations (mg/kg) in Soil.....	17
Figure 3-1.	The Oxidation Plot and Monitoring Well Layout for Performance Assessment.....	20
Figure 3-2.	Aboveground Oxidant Handling System Installed at Launch Complex 34 .....	22
Figure 3-3.	Chemical Oxidation Setup at Launch Complex 34 Showing Permanganate Storage Hopper and Mixer .....	23

Figure 3-4. Oxidant Preinjection Manifold .....	23
Figure 3-5. Schematic of the Oxidant Injection Tip Used by the Vendor .....	23
Figure 3-6. Phase 1 Injection Locations .....	24
Figure 4-1. Sampling for Performance Assessment at Launch Complex 34 .....	27
Figure 4-2. Predemonstration Soil Coring Locations (SB-13 to SB-24) in Oxidation Plot.....	29
Figure 4-3. Postdemonstration Soil Coring Locations 9SB-213 to SB-224) .....	30
Figure 4-4. Outdoor Cone Penetrometer Test Rig for Soil Coring at Launch Complex 34.....	31
Figure 4-5. Indoor Vibra-Push Rig (LD Geoprobe® Series) Used in the Engineering Service Building .....	31
Figure 4-6. Surface Emissions Testing at Launch Complex 34 .....	33
Figure 5-1. Distribution of Pre- and Postdemonstration TCE Concentrations (mg/kg) in the Oxidation Plot Soil.....	35
Figure 5-2. Representative Predemonstration (a) and Postdemonstration (b) Concentrations of TCE (mg/kg) in the Upper Sand Unit .....	39
Figure 5-3. Representative Predemonstration (a) and Postdemonstration (b) Concentrations of TCE (mg/kg) in the Middle Fine-Grained Unit....	40
Figure 5-4. Representative Predemonstration (a) and Postdemonstration (b) Concentrations of TCE (mg/kg) in the Lower Sand Unit .....	41
Figure 5-5. Distribution of Potassium Permanganate (KMnO <sub>4</sub> ) in Shallow Wells near the Engineering Service Building at Launch Complex 34 (May 2000) .....	42
Figure 5-6. Distribution of Potassium Permanganate (KMnO <sub>4</sub> ) in Intermediate Wells near the Engineering Service Building at Launch Complex 34 (May 2000) .....	43
Figure 5-7. Distribution of Potassium Permanganate (KMnO <sub>4</sub> ) in Deep Wells near the Engineering Service Building at Launch Complex 34 (May 2000) .....	44
Figure 5-8. Dissolved TCE Concentrations (µg/L) during (a) Predemonstration and (b) Postdemonstration Sampling of Shallow Wells .....	48
Figure 5-9. Dissolved TCE Concentrations (µg/L) during (a) Predemonstration and (b) Postdemonstration Sampling of Intermediate Wells .....	49
Figure 5-10. Dissolved TCE Concentrations (µg/L) during (a) Predemonstration and (b) Postdemonstration Sampling of Deep Wells.....	50
Figure 5-11. Distribution of Chloride Produced by Oxidation Technology in Shallow Wells near the Engineering Service Building at Launch Complex 34 (May 2000).....	54
Figure 5-12. Distribution of Chloride Produced by Oxidation Technology in Intermediate Wells near the Engineering Service Building at Launch Complex 34 (May 2000).....	55
Figure 5-13. Distribution of Chloride Produced by Oxidation Technology in Deep Wells near the Engineering Service Building at Launch Complex 34 (May 2000) .....	56
Figure 5-14. Water Levels Measured in Shallow Wells near the Engineering Service Building at Launch Complex 34 (April 10, 2000) .....	57
Figure 5-15. Water Levels Measured in Intermediate Wells near the Engineering Service Building at Launch Complex 34 (April 10, 2000) .....	58
Figure 5-16. Water Levels Measured in Deep Wells near the Engineering Service Building at Launch Complex 34 (April 2000) .....	58

---

Figure 5-17. Distribution of Potassium (K) Produced by Oxidation Technology in Shallow Wells near the Engineering Service Building at Launch Complex 34 (April 2000) .....	59
Figure 5-18. Distribution of Potassium (K) Produced by Oxidation Technology in Intermediate Wells near the Engineering Service Building at Launch Complex 34 (April 2000) .....	60
Figure 5-19. Distribution of Potassium (K) Produced by Oxidation Technology in Deep Wells near the Engineering Service Building at Launch Complex 34 (April 2000) .....	60
Figure 5-20. Dissolved TCE Levels ( $\mu\text{g}/\text{L}$ ) in Perimeter Wells on the Northeastern Side of the Oxidation Plot .....	61
Figure 5-21. Dissolved TCE Levels ( $\mu\text{g}/\text{L}$ ) in Perimeter Wells on the Southern Side of the Oxidation Plot .....	61
Figure 5-22. Dissolved TCE Levels ( $\mu\text{g}/\text{L}$ ) in Perimeter Wells on the Western Side of the Oxidation Plot .....	62
Figure 5-23. Dissolved TCE Levels ( $\mu\text{g}/\text{L}$ ) in Distant Wells on the Northwestern Side of the Oxidation Plot .....	62

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## Tables

Table 2-1.	Local Hydrostratigraphy at the Launch Complex 34 Site .....	8
Table 2-2.	Hydraulic Gradients and Directions in the Surficial and Confined Aquifers .....	12
Table 3-1.	Chemical Oxidation Demonstration Schedule .....	21
Table 4-1.	Summary of Performance Assessment Objectives and Associated Measurements .....	28
Table 5-1.	Estimated Total TCE and DNAPL Mass Removal by Contouring the TCE Distribution in Soil .....	44
Table 5-2.	Estimated Total TCE Mass Removal by Kriging the TCE Distribution in Soil .....	45
Table 5-3.	Estimated Total TCE and DNAPL Mass Removal by Pairwise Comparison of TCE Concentrations in Soil .....	45
Table 5-4.	Pre- and Postdemonstration Levels of Groundwater Parameters Indicative of Aquifer Quality .....	46
Table 5-5.	Postdemonstration Concentrations of Trace Metals in Groundwater at Launch Complex 34 versus the State of Florida Limits (issued May 26, 1999) .....	52
Table 5-6.	Pre- and Postdemonstration Hydraulic Conductivity in the Oxidation Plot Aquifer.....	52
Table 6-1.	Instruments and Calibration Acceptance Criteria Used for Field Measurements .....	65
Table 6-2.	List of Surrogate and Matrix Spike Compounds and Their Target Recoveries for Groundwater Analysis by the On-Site Laboratory .....	67
Table 6-3.	List of Surrogate and Laboratory Control Sample Compounds and Their Target Recoveries for Soil and Groundwater Analysis by the Off-Site Laboratory.....	67
Table 7-1.	Chemical Oxidation Cost Summary Provided by Vendor .....	69
Table 7-2.	Estimated Site Characterization Costs .....	70
Table 7-3.	Estimated Performance Assessment Costs .....	70

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## Acronyms and Abbreviations

ACL	alternative concentration limits
AFRL	Air Force Research Laboratory
ARARs	applicable or relevant and appropriate requirements
bgs	below ground surface
BOD	biological oxygen demand
CAA	Clean Air Act
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CES	Current Environmental Solutions
CMT	Core Management Team
CVOC	chlorinated volatile organic compound
CWA	Clean Water Act
DCE	<i>cis</i> -1,2-dichloroethylene
DNAPL	dense, nonaqueous-phase liquid
DO	dissolved oxygen
DoD	Department of Defense
DOE	Department of Energy
EM50	Environmental Management 50 (Program)
FDEP	(State of) Florida Department of Environmental Protection
$f_{oc}$	fraction organic carbon
FSU	Florida State University
gpm	gallon(s) per minute
HDPE	high-density polyethylene
HSWA	Hazardous and Solid Waste Amendments
IDC	Interagency DNAPL Consortium
ITRC	Interstate Technologies Regulatory Cooperation
IWR	Integrated Water Resources, Inc.
$K_{oc}$	organic carbon partitioning coefficient
LCS	laboratory control spikes
LCSD	laboratory control spike duplicates
LRPCD	Land Remediation and Pollution Control Division

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MCL	maximum contaminant level
MS	matrix spikes
MSD	matrix spike duplicates
msl	mean sea level
MSE	MSE Technology Applications, Inc.
MTBE	methyl- <i>tert</i> -butyl ether
NAAQS	National Ambient Air Quality Standards
NASA	National Aeronautics and Space Administration
NFESC	Naval Facilities Engineering Service Center
NPDES	National Pollutant Discharge Elimination System
NRMRL	National Risk Management Research Laboratory
O&M	operation and maintenance
ORD	Office of Research and Development
ORNL	Oak Ridge National Laboratory
ORP	oxidation-reduction potential
OSHA	Occupational Safety and Health Administration
POTW	publicly owned treatment works
PV	present value
PVC	polyvinyl chloride
PVDF	polyvinylidene fluoride
QA/QC	quality assurance/quality control
QAPP	Quality Assurance Project Plan
RCRA	Resource Conservation and Recovery Act
RFI	RCRA Facility Investigation
RI/FS	Remedial Investigation/Feasibility Study
RPD	relative percent difference
RSKERC	R.S. Kerr Environmental Research Center (of the U.S. EPA)
SDWA	Safe Drinking Water Act
SIP	State Implementation Plans
SITE	Superfund Innovative Technology Evaluation (Program)
STL	STL Environmental Services, Inc.
TCE	trichloroethylene
TDS	total dissolved solids
TOC	total organic carbon
U.S. EPA	United States Environmental Protection Agency
VOA	volatile organic analysis
WSRC	Westinghouse Savannah River Company

---

## 1. Introduction

This section is an introduction to the demonstration of the chemical oxidation technology for remediation of a dense, nonaqueous-phase liquid (DNAPL) source zone at Launch Complex 34, Cape Canaveral Air Station, FL. The section also summarizes the structure of this report.

### 1.1 Project Background

The goal of the project is to evaluate the technical and cost performances of the chemical oxidation technology for remediation of DNAPL source zones. Chemical oxidation was demonstrated at Launch Complex 34, Cape Canaveral Air Station, FL, where the chlorinated volatile organic compound (CVOC) trichloroethylene (TCE) is present in the aquifer as a DNAPL source. Smaller amounts of dissolved *cis*-1,2-dichloroethylene (DCE) and vinyl chloride also are present in the groundwater. The field demonstration of the technology started in September 1999 and ended in April 2000. Pre- and postdemonstration performance assessment activities were conducted before, during, and after the field demonstration.

#### 1.1.1 The Interagency DNAPL Consortium

The chemical oxidation demonstration is part of a larger demonstration of three different DNAPL remediation technologies being conducted at Launch Complex 34 with the combined resources of several U.S. government agencies. The government agencies participating in this effort have formed the Interagency DNAPL Consortium (IDC). The IDC is composed primarily of the following agencies, which are providing most of the funding for the demonstration:

- Department of Energy (DOE), Environmental Management 50 (EM50) Program
- U.S. Environmental Protection Agency (U.S. EPA), Superfund Innovative Technology Evaluation (SITE) Program
- Department of Defense (DoD), Naval Facilities Engineering Service Center (NFESC)

- National Aeronautics and Space Administration (NASA).

In the initial stages of the project, until January 2000, the Air Force Research Laboratory (AFRL) was the DoD representative on this consortium and provided significant funding. NFESC replaced AFRL in March 2000. In addition, the following organizations are participating in the demonstration by reviewing project plans and data documents, funding specific tasks, and/or promoting technology transfer:

- Patrick Air Force Base
- U.S. EPA, R.S. Kerr Environmental Research Center (RSKERC)
- Interstate Technologies Regulatory Cooperation (ITRC).

Key representatives of the various agencies constituting the IDC have formed a Core Management Team, which guides the progress of the demonstration. An independent Technical Advisory Group has been formed to advise the Core Management Team on the technical aspects of the site characterization and selection, remediation technology selection and demonstration, and the performance assessment of the technologies. The Technical Advisory Group consists of experts drawn from industry, academia, and government.

The IDC contracted MSE Technology Applications, Inc., to conduct technology vendor selection, procure the services of the three selected technology vendors, and conduct the cost evaluation of the three technologies. The IT Corporation is the selected vendor for implementing the chemical oxidation technology at Launch Complex 34. Current Environmental Solutions and Integrated Water Resources, Inc., are the vendors for the Six-Phase Heating™ (SPH™) and steam injection technologies, respectively. In addition, the IDC also contracted Westinghouse Savannah River Company to conduct the preliminary site characterization for site selection, and Florida State University to coordinate site

preparation and other field arrangements for the demonstration. Figure 1-1 summarizes the project organization for the IDC demonstration.

### 1.1.2 Performance Assessment

The IDC contracted Battelle to plan and conduct the detailed site characterization and an independent performance assessment for the demonstration of the three technologies. U.S. EPA and its contractor Tetra Tech

EM, Inc. provide quality assurance (QA) oversight and field support for the performance assessment activities. Before the field demonstration, Battelle prepared a Quality Assurance Project Plan (QAPP) that was reviewed by all the project stakeholders. This QAPP was based on the general guidelines provided by the U.S. EPA's SITE Program for test plan preparation, quality assurance, and data analysis (Battelle, 1999d). Once the demonstration started, Battelle prepared six interim reports (Battelle 1999e, and f; Battelle 2000a, b, c, and d).

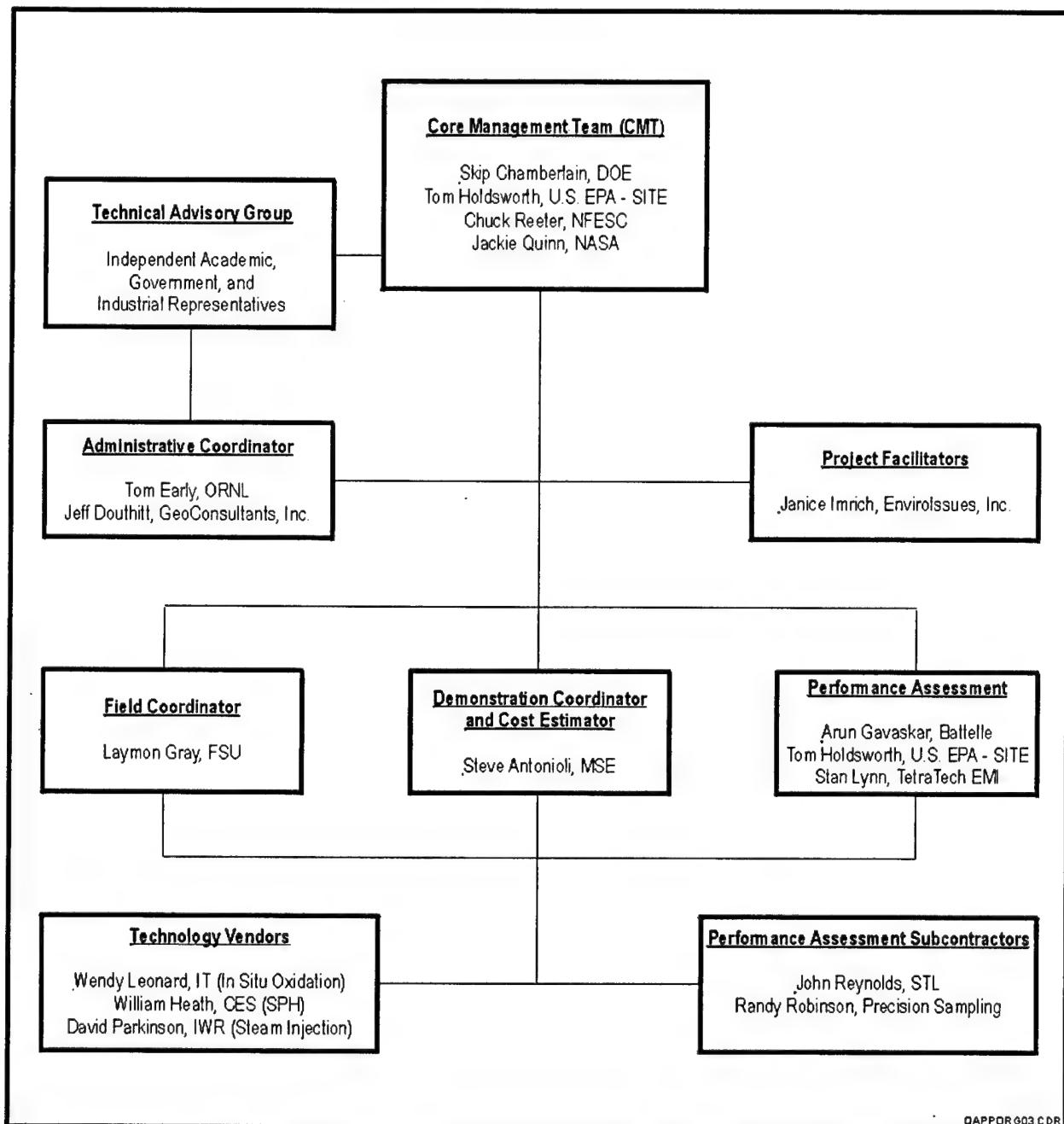


Figure 1-1. Project Organization for the IDC Demonstration at Launch Complex 34

### 1.1.3 The SITE Program

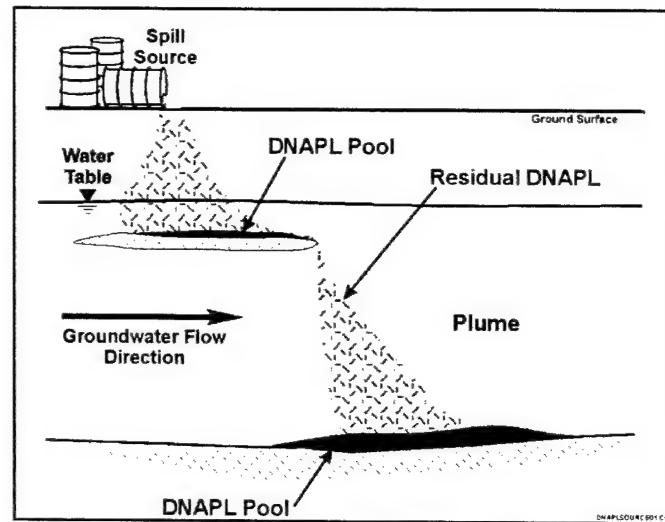
The performance assessment planning, field implementation, and data analysis and reporting for the chemical oxidation demonstration followed the general guidance provided by the U.S. EPA's SITE Program. The SITE Program was established by U.S. EPA's Office of Solid Waste and Emergency Response and the Office of Research and Development (ORD) in response to the 1986 Superfund Amendments and Reauthorization Act, which recognized a need for an "Alternative or Innovative Treatment Technology Research and Demonstration Program." ORD's National Risk Management Research Laboratory in the Land Remediation and Pollution Control Division (LRPCD), headquartered in Cincinnati, OH, administers the SITE Program. The SITE Program encourages the development and implementation of (1) innovative treatment technologies for hazardous waste site remediation and (2) innovative monitoring and measurement tools.

In the SITE Program, a field demonstration is used to gather engineering and cost data on the innovative technology so that potential users can assess the technology's applicability to a particular site. Data collected during the field demonstration are used to assess the performance of the technology, the potential need for pre- and post-processing of the waste, applicable types of wastes and waste matrices, potential operating problems, and approximate capital and operating costs.

U.S. EPA provides guidelines on the preparation of an Innovative Technology Evaluation Report at the end of the field demonstration. These reports evaluate all available information on the technology and analyze its overall applicability to other site characteristics, waste types, and waste matrices. Testing procedures, performance and cost data, and quality assurance and quality standards are also presented. This IDC report on the chemical oxidation technology demonstration at Launch Complex 34 is based on these general guidelines.

## 1.2 The DNAPL Problem

Figure 1-2 illustrates the formation of a DNAPL source at a chlorinated solvent release site. When solvent is released into the ground due to previous use or disposal practices, it travels downward through the vadose zone to the water table. Because many chlorinated solvents are denser than water, the solvent continues its downward migration through the saturated zone (assuming sufficient volume of solvent is involved) until it encounters a low-permeability layer or aquitard, on which it may form a pool. During its downward migration, the solvent leaves a trace of residual solvent in the soil pores. Many chlorinated solvents are only sparingly soluble in water;



**Figure 1-2.** Formation of a DNAPL Source in an Aquifer

therefore, they can persist as a separate phase for several years (or decades). This free-phase solvent is called DNAPL.

DNAPL in pools can often be mobilized towards extraction wells when a strong hydraulic gradient is imposed; this solvent is called mobile DNAPL. Residual DNAPL is DNAPL that is trapped in pores and cannot be mobilized towards extraction wells, regardless of how strong the applied gradient. DNAPL pools may dissolve in the groundwater flow over time, leaving behind residual DNAPL. At most sites, DNAPL pools are rare; DNAPL is often present in residual form.

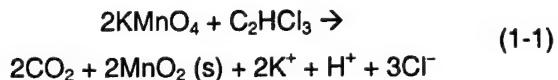
As long as there is DNAPL in the aquifer, a plume of dissolved solvent is generated. DNAPL therefore constitutes a secondary source that keeps replenishing the plume long after the primary source (leaking aboveground or buried drums, drain pipes, vadose zone soil, etc.) has been removed. Because DNAPL persists for many decades or centuries, the resulting plume also persists for many years. As recently as five years ago, DNAPL sources were difficult to find and most remedial approaches focused on plume treatment or plume control. In recent years, many chlorinated solvent-contaminated sites have been successful in identifying DNAPL sources, or at least identifying enough indicators of DNAPL. The focus is now shifting to DNAPL source removal or treatment.

Pump-and-treat systems have been the conventional treatment approach at DNAPL sites and these systems have proved useful as an interim remedy to control the progress of the *plume* beyond a property boundary or other compliance point. However, pump-and-treat systems are not economical for *DNAPL* remediation. Pools

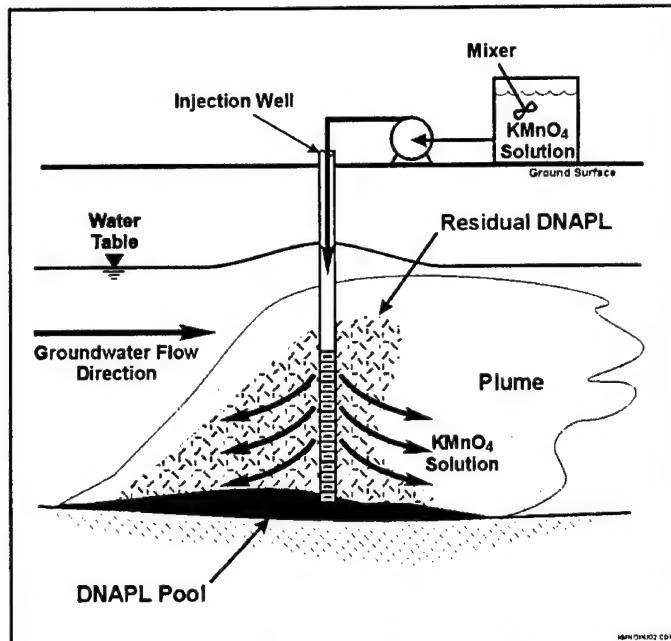
of DNAPL, which can be pumped and treated above ground, are rare. Residual DNAPL is immobile and does not migrate towards extraction wells. As with plume control, the effectiveness and cost of DNAPL remediation with pump and treat is governed by the time (decades) required for slow dissolution of the DNAPL source in the groundwater flow. An innovative approach is required to address the DNAPL problem.

### 1.3 The Chemical Oxidation Technology

Figure 1-3 illustrates the in situ application of a chemical oxidant for remediation of a DNAPL source zone. This innovative technology is based on the ability of strong oxidants to react with and destroy several types of DNAPL contaminants. Common chemicals with high oxidation potential that have been used to treat DNAPL zones are Fenton's reagent (Watts et al., 1990) and potassium permanganate (Vella et al., 1990; Gates et al., 1995; Schnarr et al., 1998). Equation 1-1 illustrates how a common contaminant, TCE, would react with potassium permanganate. TCE is oxidized to potentially nontoxic byproducts, such as carbon dioxide, manganese dioxide (solid), and chloride.



Treatment of CVOCs with oxidants has been used historically for drinking water and wastewater treatment, but the in situ use of these oxidants for DNAPL source treatment is relatively new. The stoichiometry for the complete destruction of TCE, a common DNAPL constituent, by potassium or sodium permanganate is as shown in Equation 1-1. In the absence of other organic matter, the reaction is second order and the rate is governed by the concentrations of both TCE and  $\text{MnO}_4^-$  ion. In an aquifer setting, permanganate also reacts with other reduced species, including native organic matter. The natural organic matter in an aquifer competes with the contaminant for consuming the oxidant. Therefore, the amount of oxidant required to sweep an aquifer depends on the characteristics of both the contaminants and the aquifer. In addition, geologic heterogeneities may limit the degree of contact achievable between the oxidant and the contaminant. In this respect, a longer-lived oxidant, such as permanganate, has some advantage over a short-lived oxidant, such as the hydroxyl free radical created from Fenton's reagent. Because it does not degrade as quickly as the hydroxyl free radical, permanganate can potentially sweep longer distances around the injection point and persist long enough to diffuse slowly into more difficult pores. Therefore, potassium permanganate was used as the oxidant in the IDC demonstration at Launch Complex 34.



**Figure 1-3. In Situ Chemical Oxidation of a DNAPL Source Zone**

When permanganate is applied in an injection-only mode, as was done in this demonstration, extraction of the injected fluids and their subsequent treatment and disposal/reinjection is not required. Therefore, chemical oxidation has a potential advantage over technologies that rely on enhanced mobilization, capture, and above-ground treatment of DNAPL contaminants. One concern with in situ application of permanganate has been related to the generation of manganese dioxide, a solid that could build up in the aquifer and potentially cause plugging of pores. Another concern has been the spread of dissolved manganese ( $\text{Mn}^{2+}$ ), a reduced species that is generated from manganese ( $\text{Mn}^{4+}$ ) dioxide, if and when the oxidative environment reverts to a reducing environment. Dissolved manganese is subject to a secondary (nonhealth-based) drinking water standard. A third concern relates to the potential for release of regulated metals from the aquifer formation under strong oxidizing conditions. These concerns were evaluated during the demonstration.

### 1.4 The Demonstration Site

Launch Complex 34, the site selected for this demonstration, is located at Cape Canaveral Air Station, Florida (see Figure 1-4). Launch Complex 34 was used as a launch site for Saturn rockets from 1960 to 1968. Historical records and worker accounts suggest that rocket engines were cleaned on the launch pad with chlorinated organic solvents such as TCE. Other rocket parts were cleaned on racks at the western portion of the Engineering Service Building and inside the building. Some of the

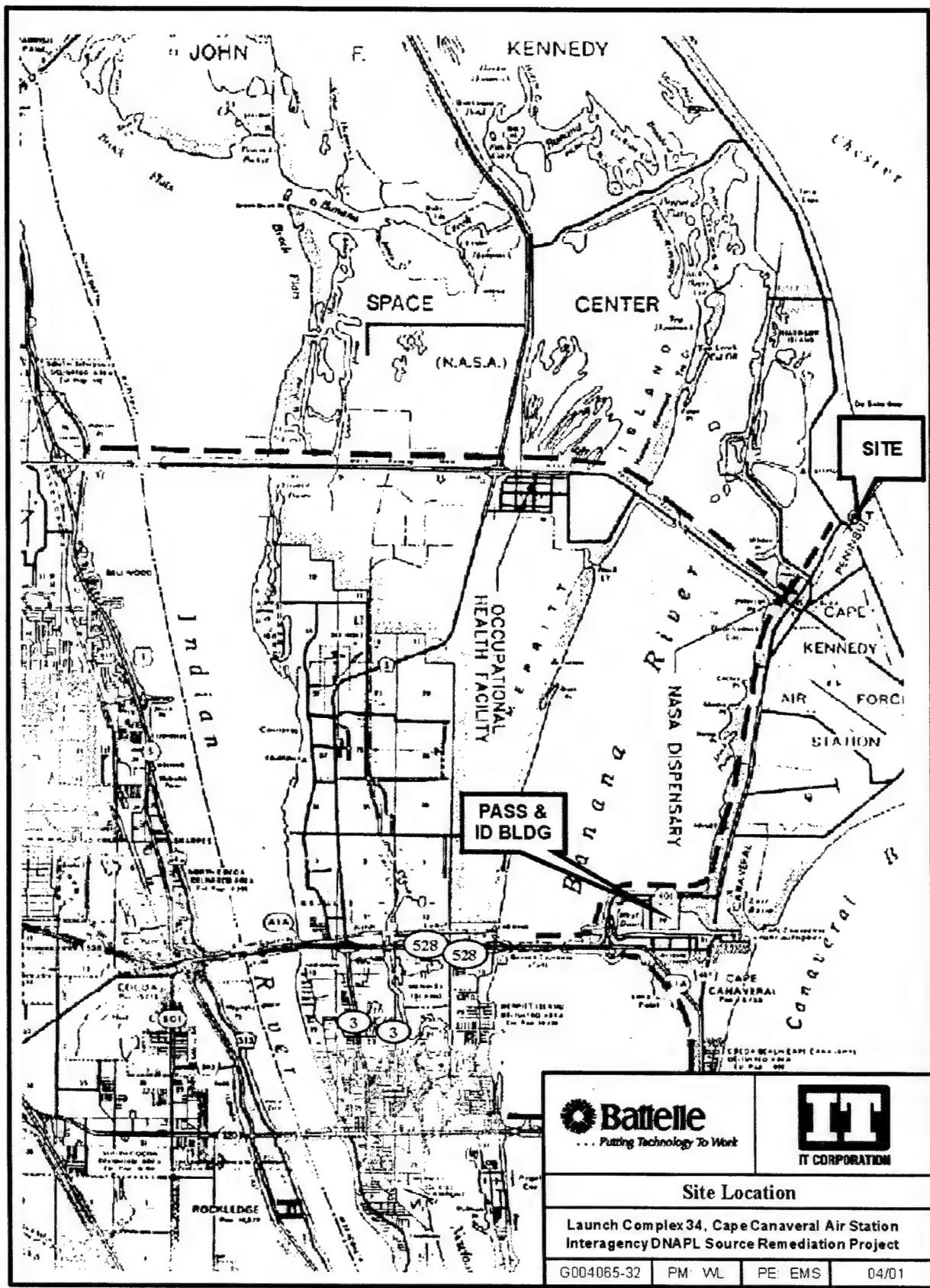


Figure 1-4. Demonstration Site Location

solvents ran off to the surface or discharged into drainage pits. The site was abandoned in 1968 and since that time much of the site has been overgrown by vegetation, although several on-site buildings remain operational.

Preliminary site characterization efforts suggested that approximately 20,600 kg (Battelle, 1999a) to 40,000 kg (Eddy-Dilek et al., 1998) of solvent could be present in the subsurface near the Engineering Service Building at Launch Complex 34. Figure 1-5 is a map of the Launch Complex 34 site at Cape Canaveral that shows the target DNAPL source area, located in the northern vicinity of the Engineering Service Building. The DNAPL source zone was large enough that the IDC and the Technical Advisory Group could assign three separate test plots encompassing different parts of this source zone. Figure 1-5 also shows the layout of the three test plots along the northern edge of the Engineering Service Building at Launch Complex 34. The Oxidation Plot is the easternmost of these plots. Figure 1-6 is a photo-

graph looking southward towards the three test plots and the Engineering Service Building. All three test plots lie partly under the Engineering Service Building so as to encompass the portion of the DNAPL source under the building.

## 1.5 Technology Evaluation Report Structure

The chemical oxidation technology evaluation report starts with an introduction to the project organization, the DNAPL problem, the technology demonstrated, and the demonstration site (Section 1). The rest of the report is organized as follows:

- Site Characterization (Section 2)
- Technology Operation (Section 3)
- Performance Assessment Methodology (Section 4)

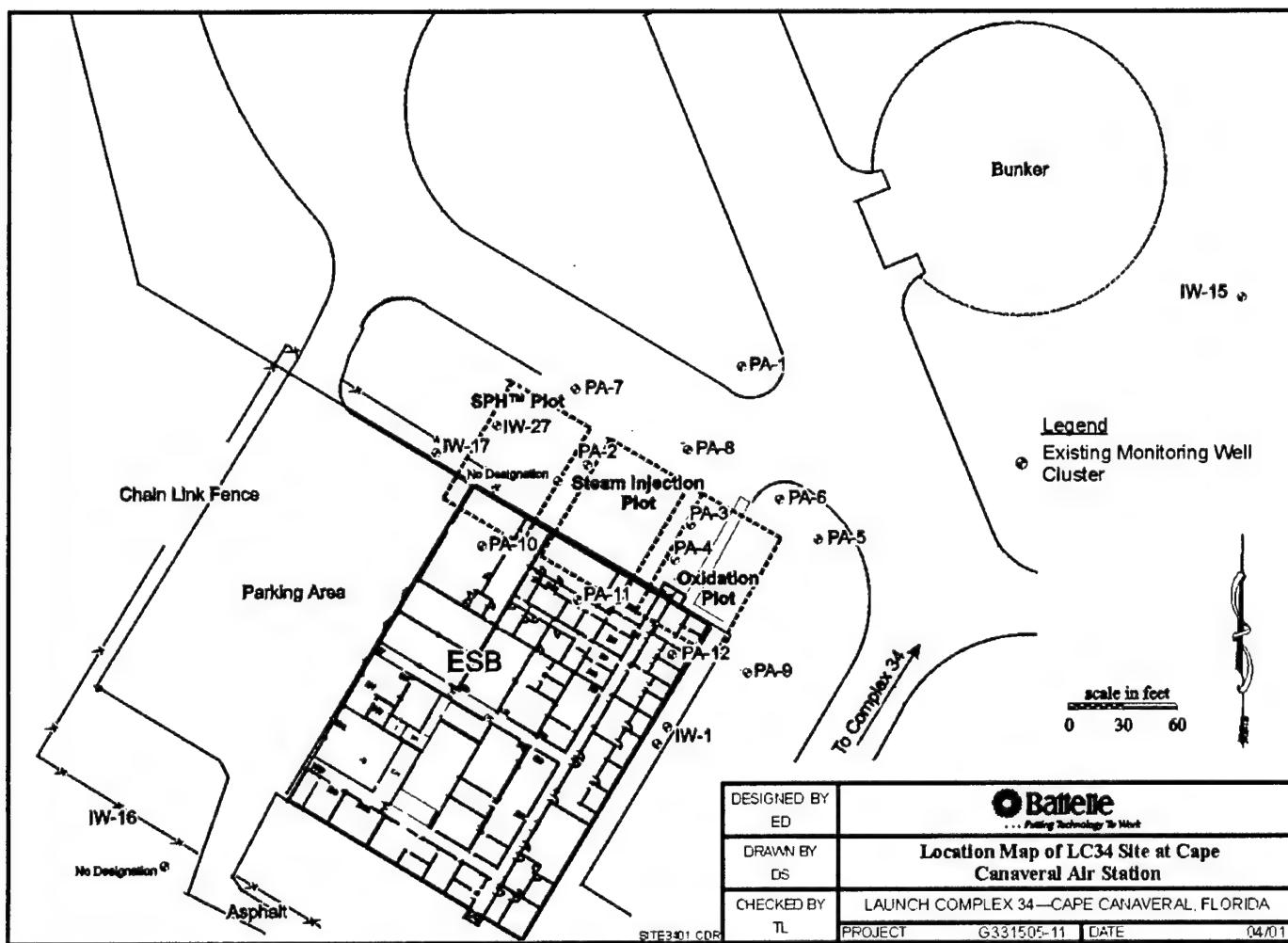
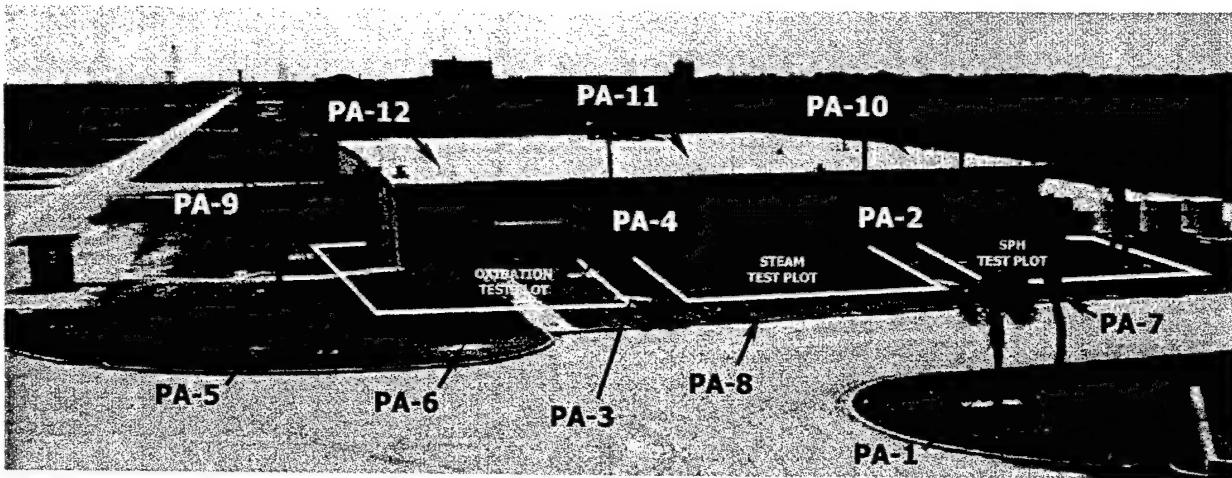


Figure 1-5. Location Map of Launch Complex 34 Site at Cape Canaveral Air Station



**Figure 1-6.** Looking Southward towards Launch Complex 34, the Engineering Service Building, and the Three Test Plots

- Performance Assessment Results and Conclusions (Section 5)
- Quality Assurance (Section 6)
- Economic Analysis of the Technology (Section 7)
- Technology Applications Analysis (Section 8)
- References (Section 9).
- Performance Assessment Methods (Appendix A)
- Hydrogeologic Measurements (Appendix B)
- CVOC Measurements (Appendix C)
- Inorganic and Other Parameters (Appendix D)
- Microbiological Assessment (Appendix E)
- Surface Emissions Testing (Appendix F)
- Quality Assurance/Quality Control (QA/QC) Information (Appendix G)
- Economic Analysis Information (Appendix H).

Supporting data and other information are presented in the appendices to the report. The appendices are organized as follows:

## 2. Site Characterization

This section provides a summary of the hydrogeology and chemistry of the site based on the data compilation report (Battelle, 1999a), the additional site characterization report (Battelle, 1999b), and the predemonstration characterization report (Battelle, 1999c).

### 2.1 Hydrogeology of the Site

A surficial aquifer and a confined (i.e., intermediate) aquifer comprise the major aquifers in the Launch Complex 34 area, as described in Table 2-1. The surficial aquifer extends from the water table to approximately 45 ft below ground surface (bgs) in the Launch Complex 34 area. A clay confining unit separates the surficial aquifer from the underlying confined aquifer.

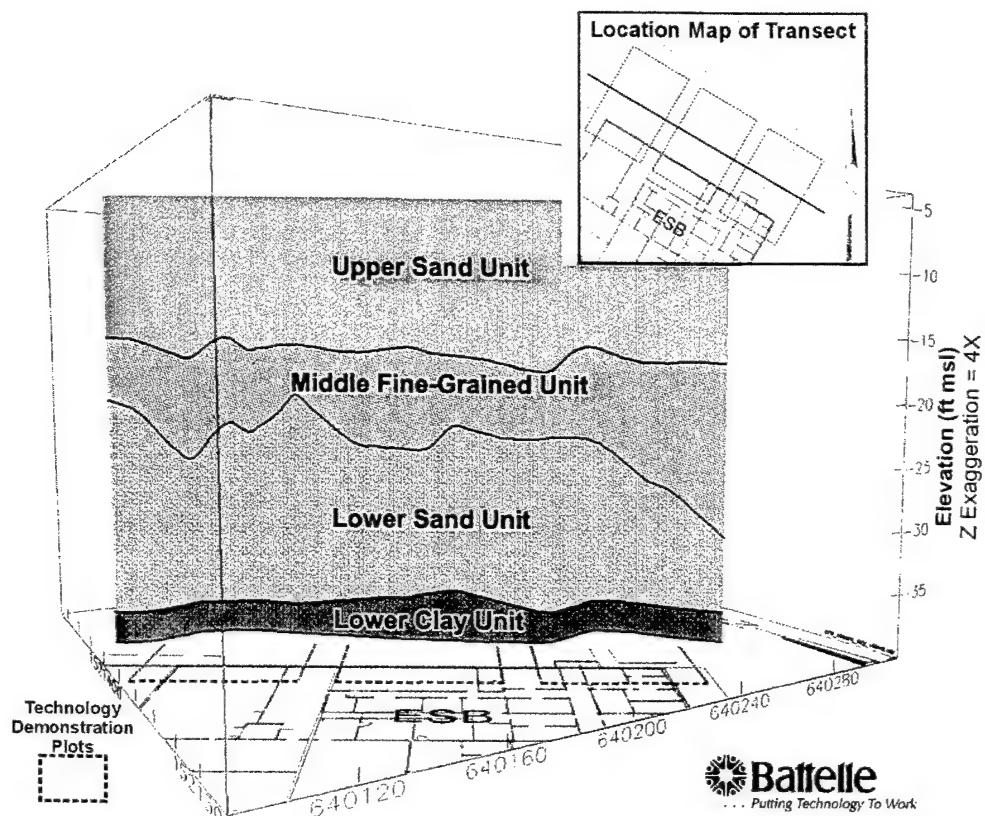
Figures 2-1 and 2-2 are two geologic cross sections, one along the east-west direction across the middle of the three test plots and the other along the north-south direction across the middle of the Oxidation Plot. As seen in these figures, the surficial aquifer is subclassified as having an Upper Sand Unit, a Middle Fine-Grained Unit, and a Lower Sand Unit. The Upper Sand Unit extends from ground surface to approximately 15 to 20 ft bgs and consists of unconsolidated, gray fine sand and shell fragments. The Middle Fine-Grained Unit is a layer of gray, fine-grained silty/clayey sand that exists between about 20 and 35 ft bgs. In general, this unit contains soil

that is finer-grained than the Upper Sand Unit and Lower Sand Unit, and varies in thickness from about 10 to 20 ft. The Middle Fine-Grained Unit is thicker in the northern portions of the test plots and appears to become thinner in the southern and western portions of the test area (under the Engineering Service Building and in the SPH™ plot). Below the Middle Fine-Grained Unit is the Lower Sand Unit, which consists of gray fine to medium-sized sand and shell fragments. The unit contains isolated fine-grained lenses of silt and/or clay. Figure 2-2 shows a stratigraphic cross section through the demonstration area.

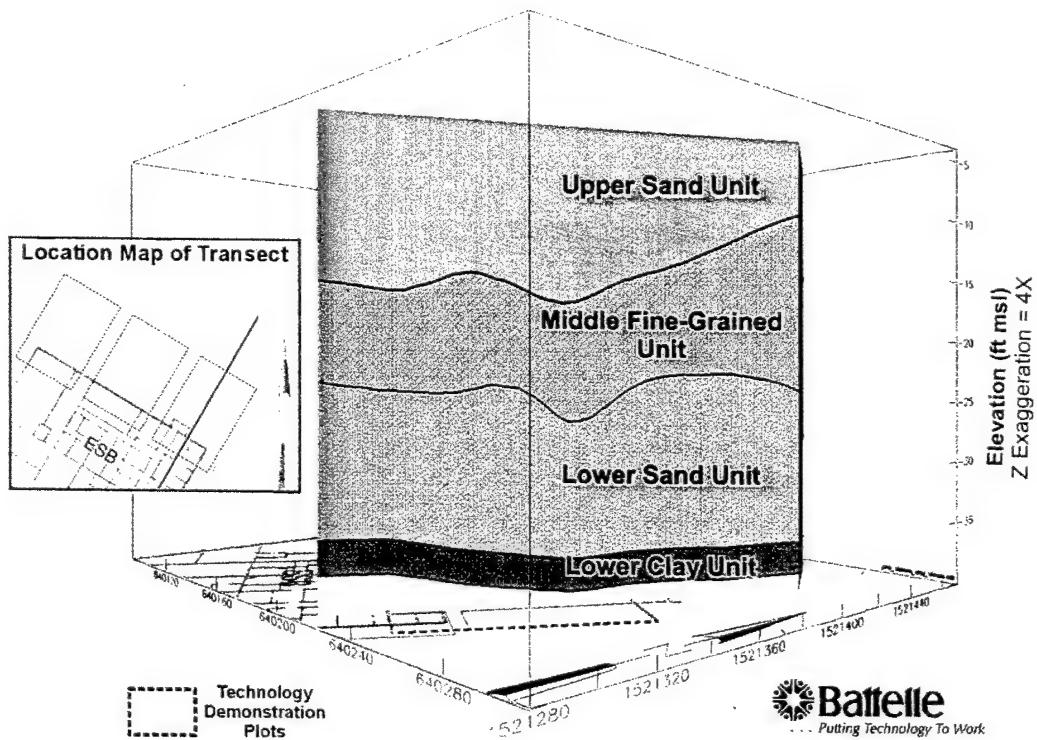
A 1- to 3-ft-thick confining layer exists at approximately 45 ft bgs in the Launch Complex 34 area. The layer consists of greenish-gray sandy clay. The confining unit (i.e., the Lower Clay Unit) was encountered in borings across the Launch Complex 34 site, and it appears to be a pervasive unit. However, the unit is fairly thin (around 1 ft thick) in some areas. Site characterization data (Battelle, 1999a and b; Eddy-Dilek et al., 1998) suggest that the surface of the Lower Clay Unit is fairly flat with slight topography. A depression appears to exist near the northeast corner of the Engineering Service Building. The thickness of the confining unit is uncertain, because most core pushing was stopped when the clay unit was encountered, so as to prevent groundwater flow between the confined aquifer and the overlying surficial aquifer.

**Table 2-1.** Local Hydrostratigraphy at the Launch Complex 34 Site

Hydrostratigraphic Unit	Thickness (ft)	Sediment Description	Aquifer Description
Surficial Aquifer	Upper Sand Unit	15-20	Gray fine sand and shell fragments
	Middle Fine-Grained Unit	5-15	Gray, fine-grained silty/clayey sand
	Lower Sand Unit	10-20	Gray fine to medium-sized sand and shell fragments
Lower Clay Unit	1-3	Greenish-gray sandy clay	Thin low-permeability confining unit
Confined Aquifer	>40	Gray fine to medium-sized sand, clay, and shell fragments	Confined, brackish



**Figure 2-1.** East-West Geologic Cross Section through the Three Test Plots



**Figure 2-2.** North-South Geologic Cross Section through the Oxidation Plot

The confined aquifer underlies the confining unit. The aquifer consists of gray fine to medium-sized sand, clay, and shell fragments. Water levels from wells in the aquifer were measured at approximately 4 to 5 ft bgs, suggesting that the aquifer is confined. Few cores were advanced below the confined aquifer. The thickness of the unit is greater than 40 ft.

Water level surveys were performed in the surficial aquifer in May 1997, December 1997, June 1998, October 1998, and March 1999. Water table elevations in the surficial aquifer were between about 1 and 5 ft mean sea level (msl). In general, the surveys suggest that water levels form a radial pattern with highest elevations under the Engineering Service Building. Figure 2-3 shows a water level map from June 1998. The gradient and flow directions vary over time at the site. Table 2-2 summarizes the hydraulic gradients and their directions near the Engineering Service Building. The gradient ranged from 0.00009 to 0.0007 ft/ft. The flow direction varied from north-northeast to south-southwest.

The surficial aquifer is unconfined above the Middle Fine-Grained Unit and semiconfined below the Middle Fine-Grained Unit. Predemonstration water level measurements in all three aquifer units — Upper Sand Unit, Middle Fine-Grained Unit, and Lower Sand Unit — indicate a relatively flat hydraulic gradient in the localized setting of the three test plots, as seen in Figures 2-4 to 2-6 (Battelle, 1999c). On a regional scale, mounding of water levels near the Engineering Service Building generates a radial gradient; the regional gradient across the test plots appears to be toward the northeast (see Figure 2-3). Probable discharge points for the aquifer include wetland areas, the Atlantic Ocean, and/or the Banana River. Water levels from wells screened in the Lower Sand Unit usually are slightly higher than the water levels from the Upper Sand Unit and/or the Middle Fine-Grained Unit. The flow system may be influenced by local recharge events, resulting in the variation in the gradients. Recharge to the surficial aquifer is from infiltration of precipitation through surface soils to the aquifer.

In general, predemonstration slug tests show that the Upper Sand Unit is more permeable than the underlying units, with hydraulic conductivity ranging from 4.0 to 5.1 ft/day in the shallow wells at the site (Battelle, 1999c). The hydraulic conductivity of the Middle Fine-Grained Unit ranges from 1.4 to 6.4 ft/day in the intermediate wells; measured conductivities probably are higher than the actual conductivity of the unit because the well screens include portions of the Upper Sand Unit. The hydraulic conductivity of the Lower Sand Unit ranged from 1.3 to 2.3 ft/day. Porosity averaged 0.26 in the Upper Sand Unit, 0.34 in the Middle Fine-Grained Unit, 0.29 in the Lower Sand Unit, and 0.44 in the Lower

Clay Unit. The bulk density of the aquifer materials averaged 1.59 g/cm<sup>3</sup> (Battelle, 1999b). Groundwater temperatures ranged from 22.4 to 25.7°C during a March 1999 survey.

A water level survey in the confined aquifer was performed in December 1997, June 1998, and October 1998. Water level elevations were measured at approximately 1 to 5 ft msl, and formed a pattern similar to the pattern formed by surficial aquifer water levels. Groundwater elevations are well above the confining unit, indicating that the aquifer is confined. The gradient in the confined aquifer is positioned in a similar direction to the surficial aquifer. The flow direction varies from east to south-southwest. In general, water levels in the confined aquifer are higher than those in the surficial aquifer, suggesting an upward vertical gradient. Recharge to the aquifer may occur by downward leakage from overlying aquifers or from direct infiltration inland where the aquifer is unconfined. Schmalzer and Hinkle (1990) suggest that saltwater intrusion may occur in intermediate aquifers such as the confined aquifer.

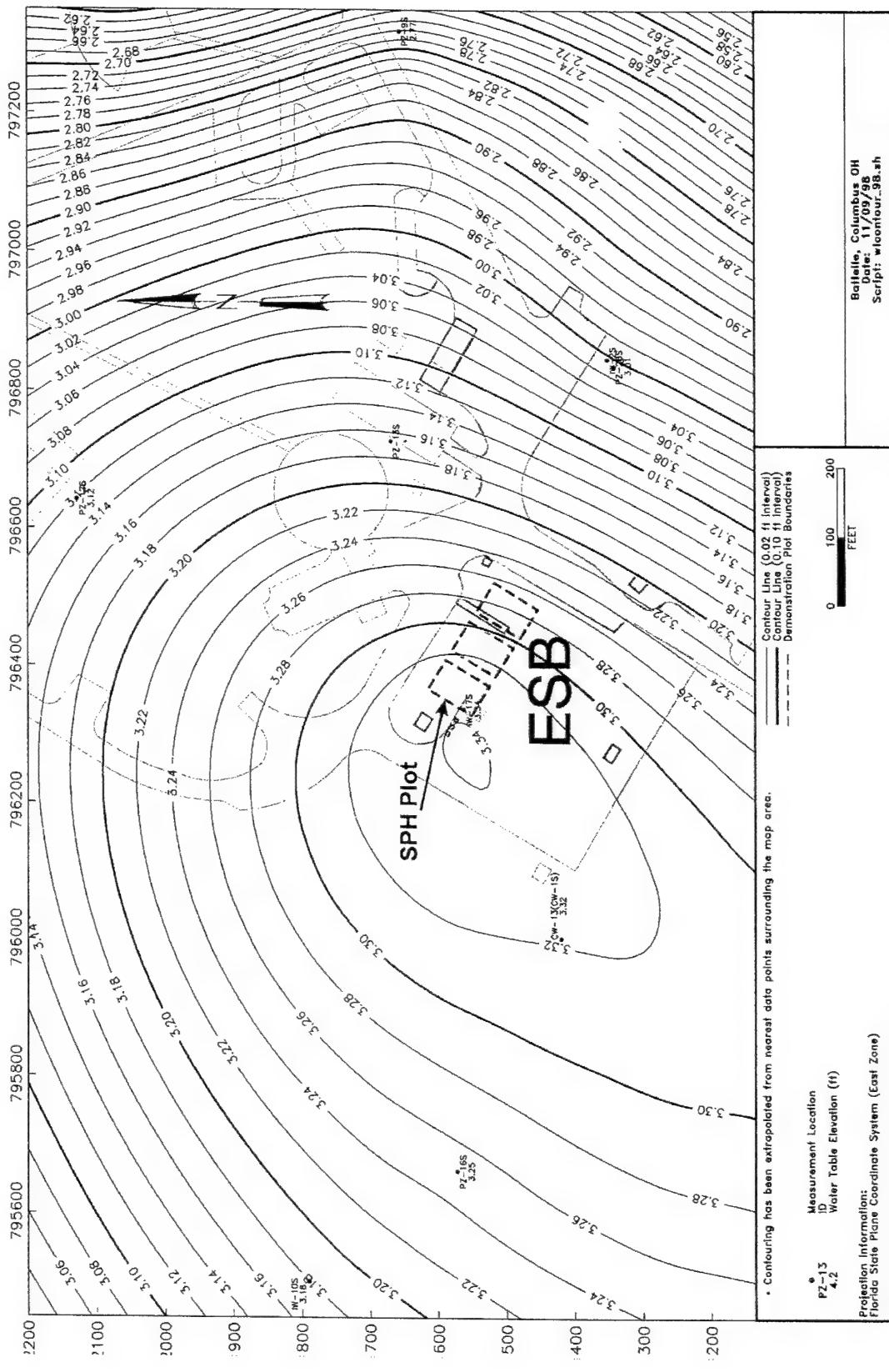
Other notable hydrologic influences at the site include drainage and recharge. Paved areas, vegetation, and topography affect drainage in the area. No streams exist in the site area. Engineered drainage at the site consists of ditches that lead to the Atlantic Ocean or swampy areas. Permeable soils exist from the ground surface to the water table and drainage is excellent. Water infiltrates directly to the water table.

## 2.2 Surface Water Bodies at the Site

The major surface water body in the area is the Atlantic Ocean, located to the east of Launch Complex 34. To determine the effects of surface water bodies on the groundwater system, water levels were monitored in 12 piezometers over 50 hours for a tidal influence study during Resource Conservation and Recovery Act (RCRA) Facility Investigation (RFI) activities (G&E Engineering, Inc., 1996). All the piezometers used in the study were screened in the surficial aquifer. No detectable effects from the tidal cycles were measured, suggesting that the surficial aquifer and the Atlantic Ocean are not well connected hydraulically. However, the Atlantic Ocean and the Banana River seem to act as hydraulic barriers or sinks, as groundwater likely flows toward these surface water bodies and discharges into them.

## 2.3 TCE/DNAPL Contamination in the Oxidation Plot and Vicinity

Figures 2-7 to 2-9 show representative predemonstration distributions of TCE, the primary contaminant at Launch Complex 34, in the shallow, intermediate, and deep wells



**Figure 2-3.** Water-Level Map from June 1998

**Table 2-2.** Hydraulic Gradients and Directions in the Surficial and Confined Aquifers

Hydrostratigraphic Unit	Sampling Date	Hydraulic Gradient	Gradient Direction
Surficial Aquifer	May 1997	0.00009	SW
	December 1997	0.0001	SSW
	June 1998	0.0006	WNW
	October 1998	0.0007	NNE
	March 1999	undefined	undefined
Confined Aquifer	December 1997	0.0008	S
	June 1998	0.0005	E
	October 1998	0.00005	SSW

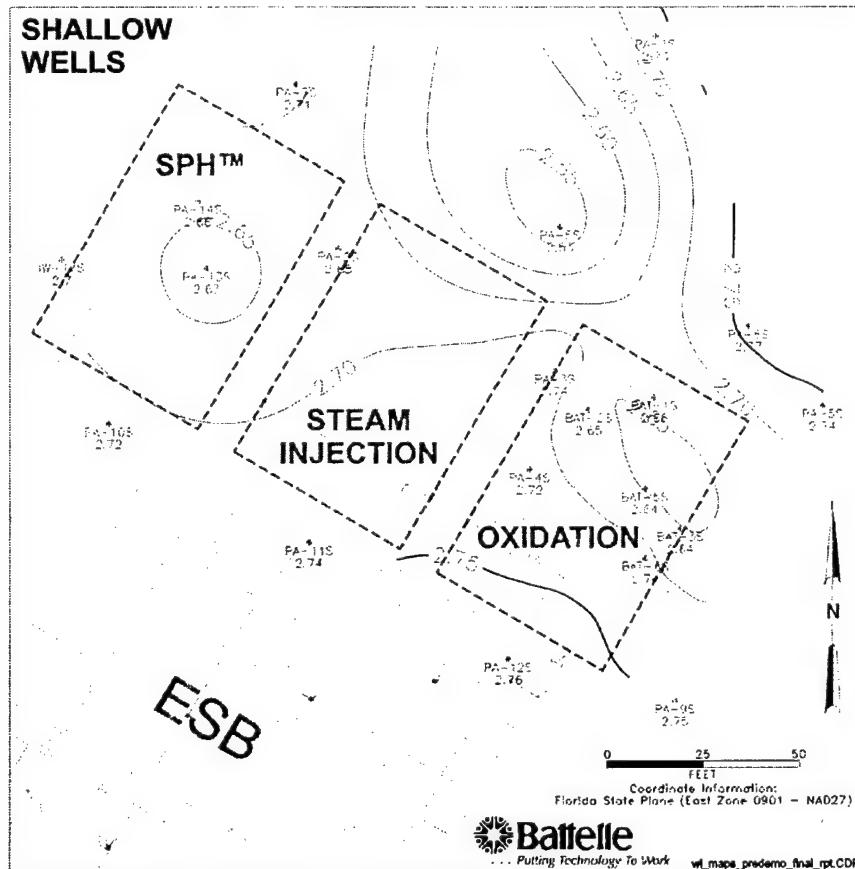
wells (Battelle, 1999c). No free-phase solvent was visible in any of the wells during the predemonstration sampling; however, groundwater analysis in many wells shows TCE at levels near or above its solubility, indicating the presence of DNAPL at the site. Lower levels of *cis*-1,2 DCE and vinyl chloride are also present in the aquifer, indicating some historical natural attenuation of TCE. Groundwater sampling indicates that the highest levels of TCE are in the Lower Sand Unit (deep wells) and closer to the Engineering Service Building.

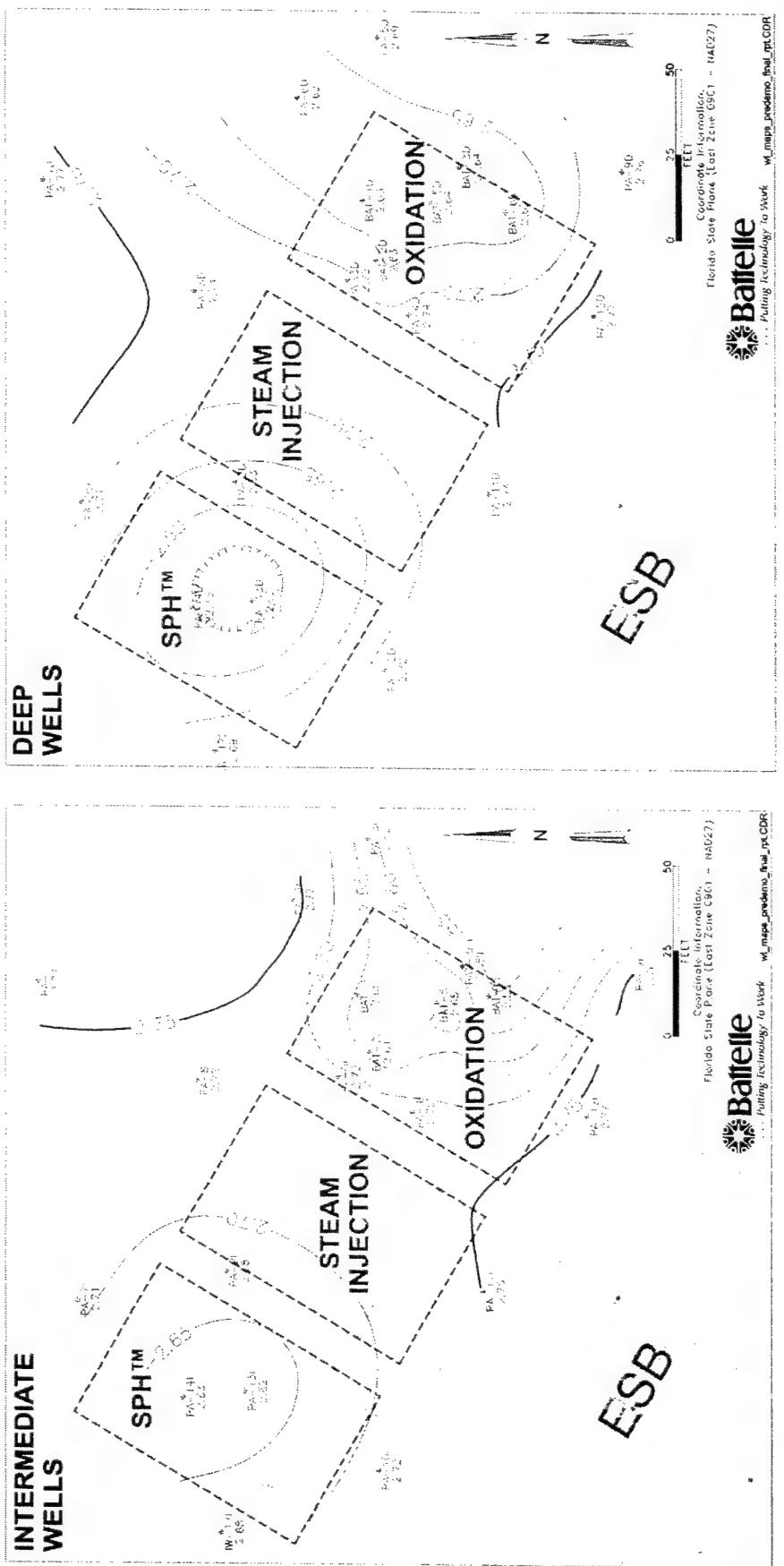
Figures 2-10 to 2-12 show representative predemonstration horizontal distributions of TCE in soil from the Upper Sand Unit, Middle Fine-Grained Unit, and Lower Sand Unit (Battelle, 1999c). TCE levels are highest in the Lower Sand Unit and concentrations indicative of DNAPL extend under the building. As seen in the vertical cross section in Figure 2-13, much of the DNAPL is present in the Middle Fine-Grained Unit and the Lower Sand Unit.

The predemonstration soil sampling indicated that approximately 6,122 kg of TCE was present in the Oxidation Plot before the demonstration (Battelle, 1999c). Approximately 5,039 kg of this TCE may occur as DNAPL, based on a threshold TCE concentration of about 300 mg/kg in the soil. This threshold concentration was determined by estimating the maximum amount of TCE that can occur in the dissolved and adsorbed phases, given the porosity and organic matter content of the soil. The portion of the measured total TCE in soil that exceeds the amount of TCE in the dissolved and adsorbed phases is DNAPL.

The threshold TCE concentration was calculated as follows:

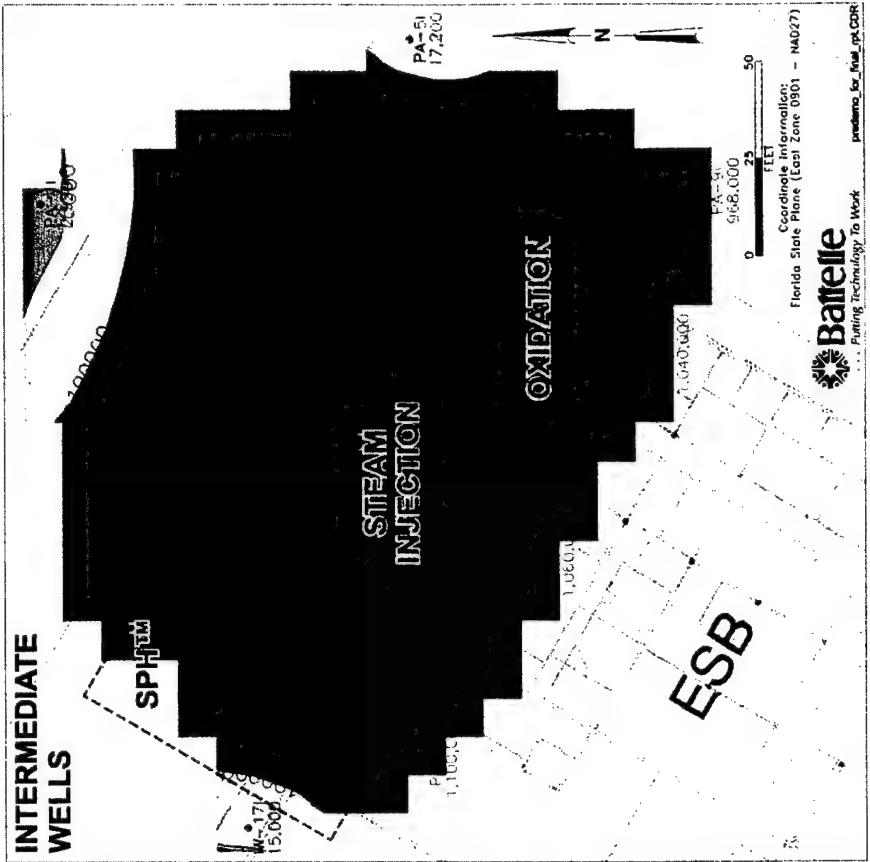
$$C_{\text{sat}} = \frac{C_{\text{water}} (K_d \rho_b + n)}{\rho_b} \quad (2-1)$$



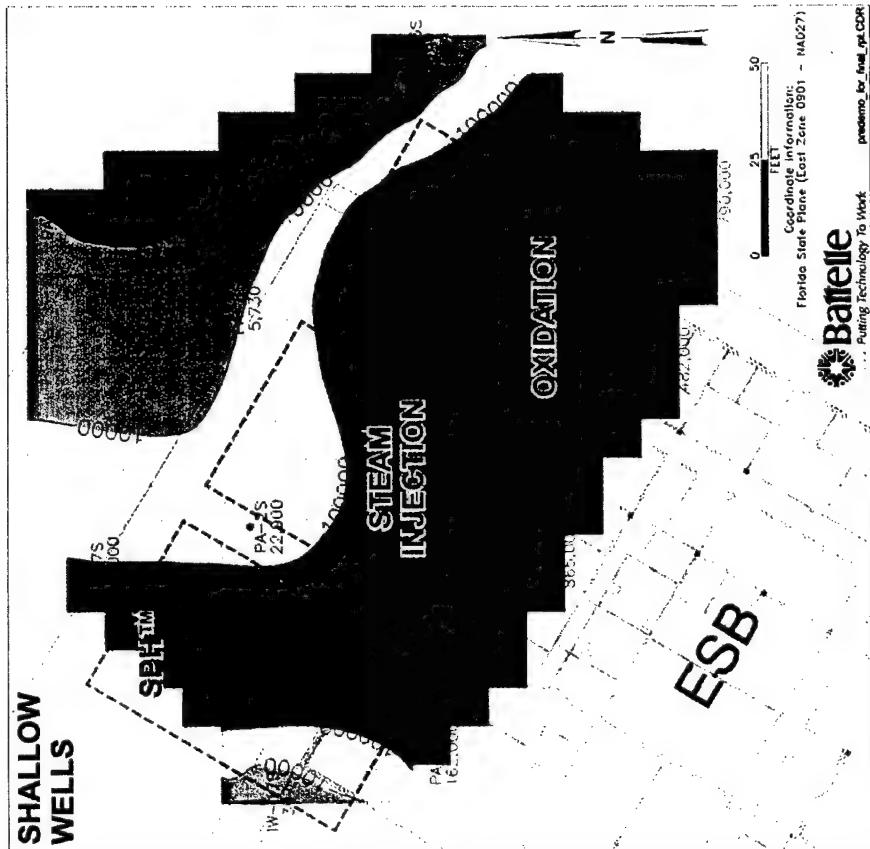


**Figure 2-5.** Predemonstration Water Levels (as Elevations msl) in Intermediate Wells at Launch Complex 34

**Figure 2-6.** Predemonstration Water Levels (as Elevations msl) in Deep Wells at Launch Complex 34



**Figure 2-8.** Predemonstration Dissolved TCE Concentrations ( $\mu\text{g/L}$ ) in Intermediate Wells at Launch Complex 34



**Figure 2-7.** Predemonstration Dissolved TCE Concentrations ( $\mu\text{g/L}$ ) in Shallow Wells at Launch Complex 34

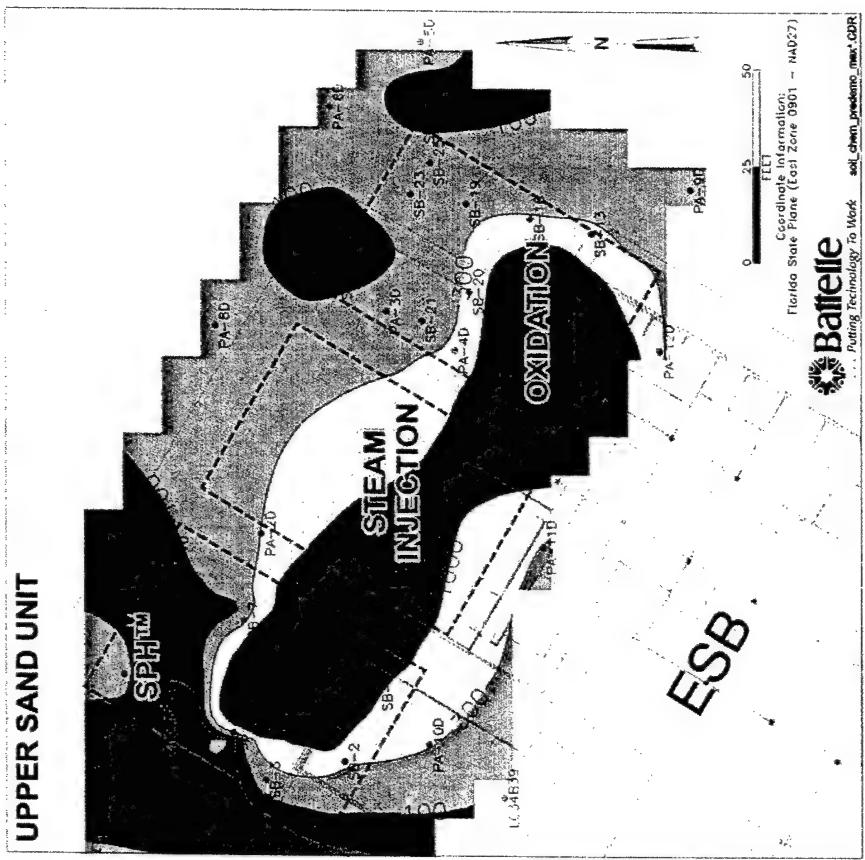


Figure 2-10. Predemonstration TCE Concentrations (mg/kg) in the Upper Sand Unit Soil at Launch Complex 34

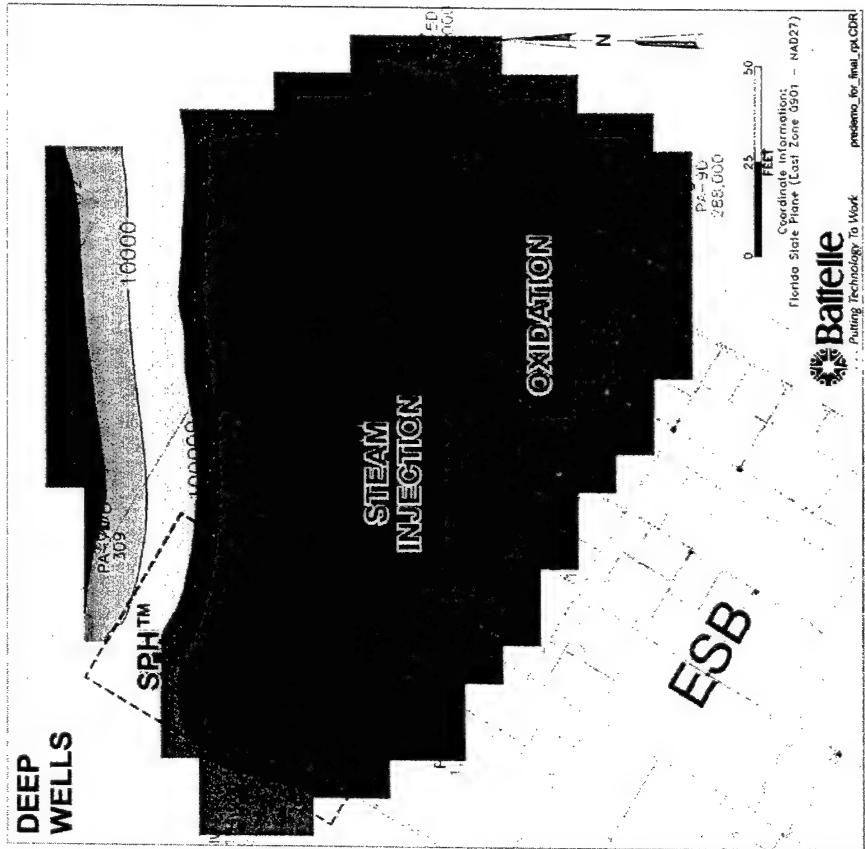
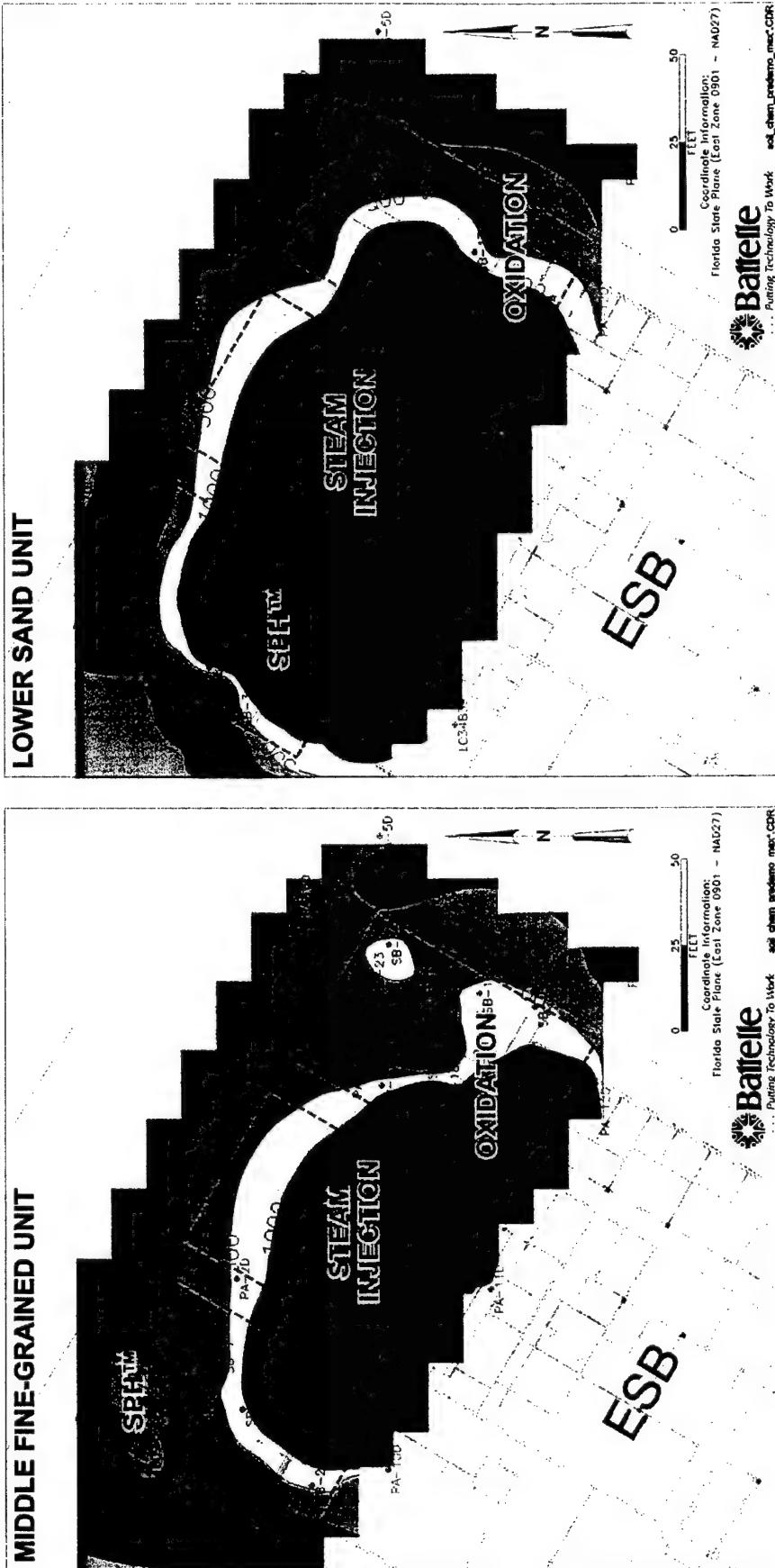
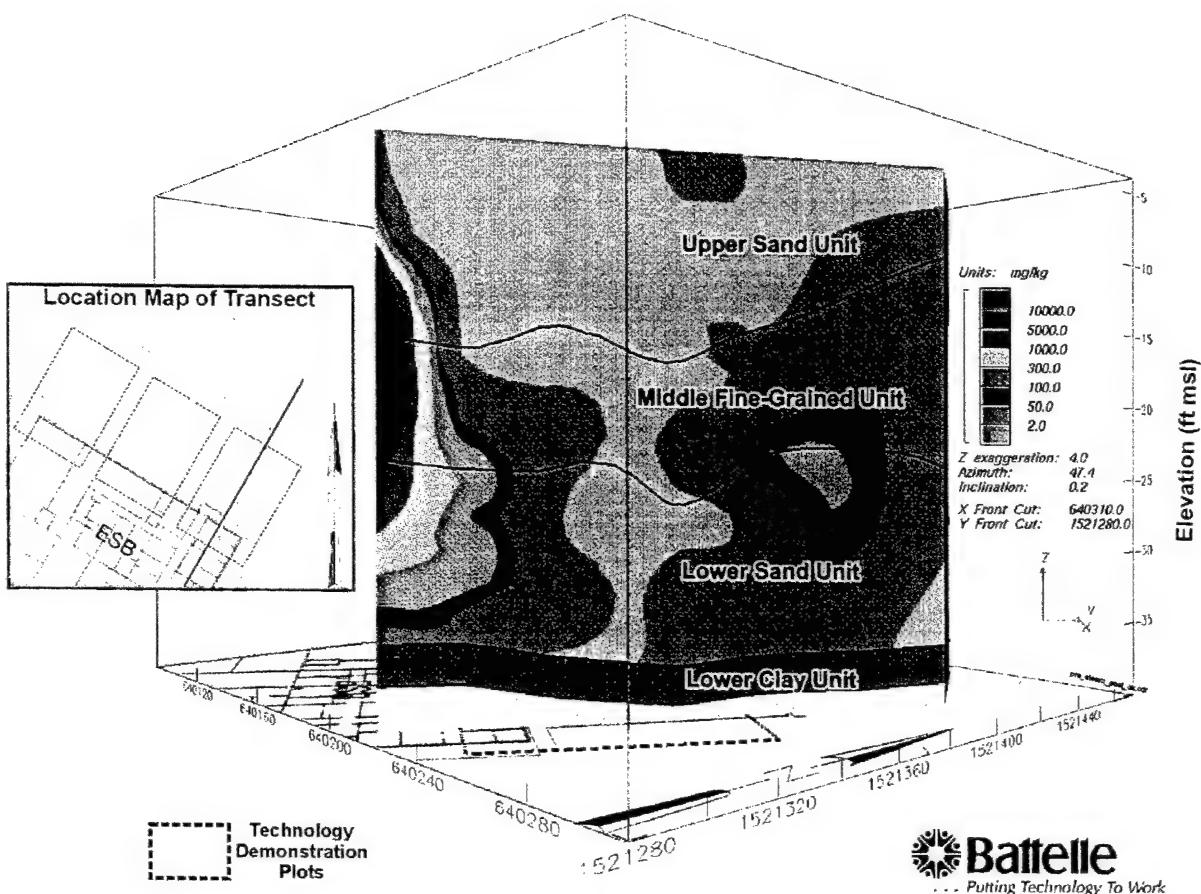


Figure 2-9. Predemonstration Dissolved TCE Concentrations ( $\mu\text{g/L}$ ) in Deep Wells at Launch Complex 34



**Figure 2-12.** Predemonstration TCE Concentrations (mg/kg) in the Lower Sand Unit Soil at Launch Complex 34

**Figure 2-11.** Predemonstration TCE Concentrations (mg/kg) in the Middle Fine-Grained Unit Soil at Launch Complex 34



**Figure 2-13.** Vertical Cross Section through Oxidation Plot Showing TCE Concentrations (mg/kg) in Soil

where  $C_{sat}$  = maximum TCE concentration in the dissolved and adsorbed phases (mg/kg)  
 $C_{water}$  = TCE solubility (mg/L) = 1,100  
 $\rho_b$  = bulk density of soil ( $\text{g}/\text{cm}^3$ ) = 1.6  
 $n$  = porosity (unitless) = 0.3  
 $K_d$  = partitioning coefficient of TCE in soil [ $(\text{mg}/\text{kg})/(\text{mg}/\text{L})$ ], equal to ( $f_{oc} \cdot K_{oc}$ )  
 $f_{oc}$  = fraction organic carbon (unitless)  
 $K_{oc}$  = organic carbon partition coefficient [ $(\text{mg}/\text{kg})/(\text{mg}/\text{L})$ ].

The native organic carbon content of the Launch Complex 34 soil is relatively low and the threshold TCE concentration is driven by the solubility of TCE in the pore water. Based on Equation (2-1), the threshold TCE concentration for this site was approximated to 300 mg/kg.

TCE with concentrations below this threshold was considered dissolved phase; at or above this threshold, the TCE was considered to be DNAPL. In Figures 2-10 to 2-13, the colors yellow to red indicate presence of DNAPL. As described in Section 4.1.1, contouring software from

EarthVision was used to divide the plot into isoconcentration shells. The TCE concentration in each shell was multiplied by the volume of the shell and the bulk density of the soil to obtain a total TCE mass. The TCE mass in the shells containing concentrations greater than 300 mg/kg was used to determine the DNAPL mass in the plot. Section 5.1 contains a more detailed description of the TCE/DNAPL mass estimation procedures for the Oxidation Plot.

## 2.4 Aquifer Quality/Geochemistry

Appendix A.3 lists the various aquifer parameters measured and the standard methods used to analyze them. Appendix D contains the results of the predemonstration groundwater analysis. Predemonstration groundwater field parameters were measured in several wells in the demonstration area in August 1999 (Battelle, 1999c). The pH was relatively constant with depth, and ranged from 7.0 to 7.6. Measured dissolved oxygen (DO) levels were mostly less than 1 mg/L in deep wells, indicating that the aquifer was anaerobic. Oxidation-reduction potential (ORP) from all the sampled wells ranged from -165 to

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-22 millivolts (mV). Total organic carbon (TOC) concentrations in soil samples ranged from 0.9 to 1.7%; much of this TOC is probably TCE/DNAPL, as the samples were collected from the DNAPL source region.

Inorganic groundwater parameters were tested in August 1999 in select wells to determine the predemonstration quality of the groundwater in the target area (Battelle, 1999c). Inorganic parameters in the groundwater at Launch Complex 34 are summarized as follows:

- Total dissolved solids (TDS) concentrations increased sharply with depth, suggesting that the water becomes more brackish with depth. The TDS levels ranged from 387 to 1,550 mg/L. Chloride concentrations ranged from 38 to 752 mg/L and increased sharply with depth, indicating some saltwater intrusion in the deeper layers. These high levels of chloride made a chloride mass balance difficult during the performance assessment.
- Alkalinity levels ranged from 204 to 323 mg/L and showed little trend with depth or distance.

- Iron concentrations ranged from <0.05 to 0.5 mg/L in the groundwater, and manganese concentrations ranged from <0.015 to 1.1 mg/L with little vertical or lateral trend.
- Calcium concentrations ranged from 41 to 88 mg/L and magnesium concentrations ranged from 53 to 84 mg/L.
- Sulfate concentrations were between 29 and 138 mg/L and showed no discernable trends. Nitrate concentrations were below detection.

## 2.5 Aquifer Microbiology

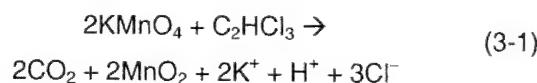
A separate exploratory microbiological study was conducted in the predemonstration and postdemonstration aquifer in the Oxidation Plot under a Work Plan prepared by Battelle and Lawrence Berkeley National Laboratory (Battelle, 2000d). The approach and preliminary results of this study are presented in Appendix E.

### **3. Technology Operation**

This section describes how the chemical oxidation technology was implemented at Launch Complex 34.

#### **3.1 In Situ Chemical Oxidation Concept**

Section 1.3 describes the in situ chemical oxidation concept. In an in situ application (see Figure 1-3 in Section 1.3), a chemical oxidant is injected in the subsurface, where it contacts target contaminants and oxidizes them. The main advantage of this technology is that, in many cases, target contaminants can be oxidized to potentially nontoxic products in the ground itself. The benefits of chemical oxidation have been known in the drinking water and wastewater treatment industry for many years. It has recently emerged as a promising option for in situ treatment of contaminated aquifers, especially DNAPL source zones. The oxidant used during the demonstration at Launch Complex 34 was industrial-grade potassium permanganate. The stoichiometric reaction of permanganate with TCE, the primary contaminant at the site, is shown in Equation 3-1.



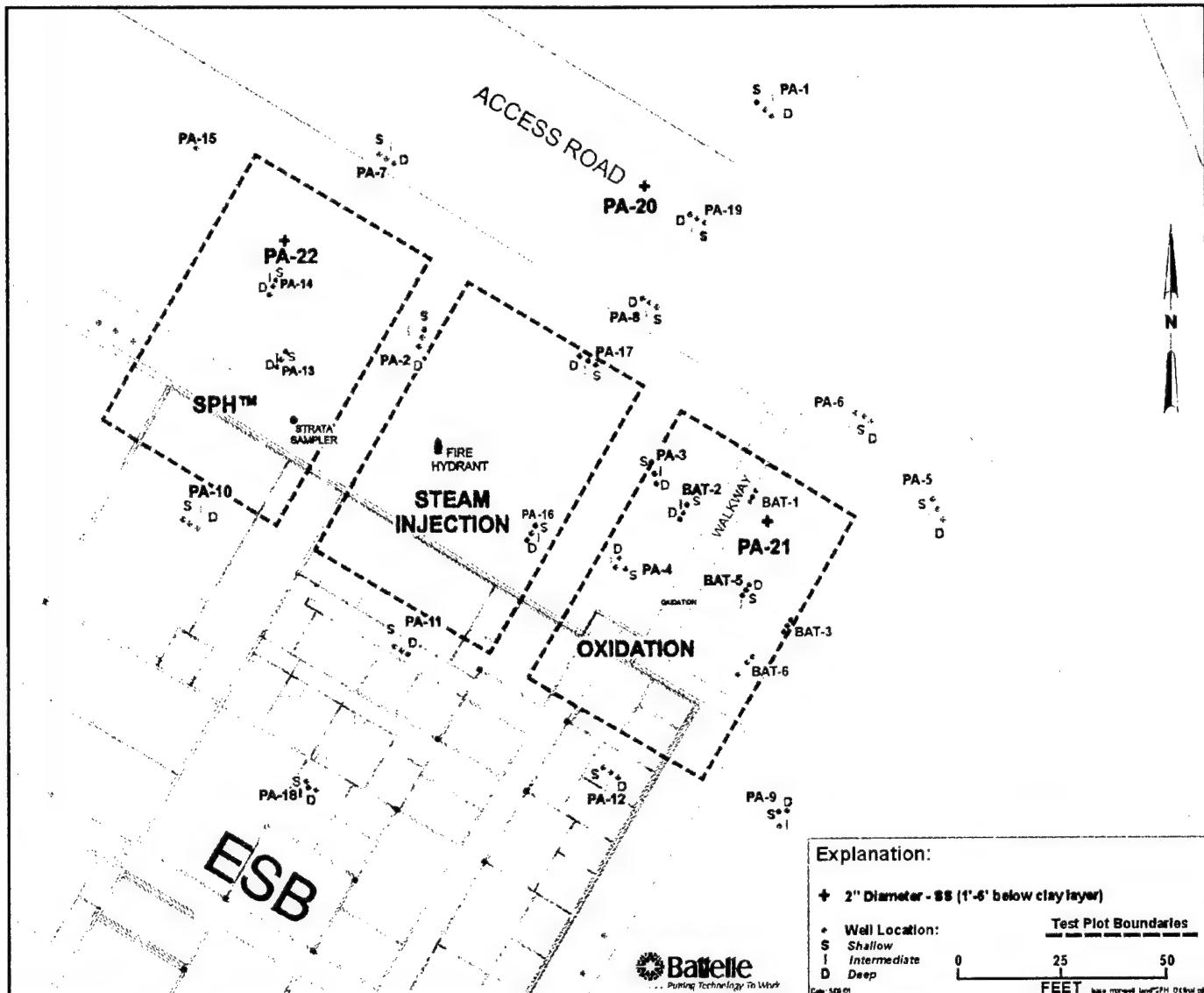
#### **3.2 Application of Chemical Oxidation at Launch Complex 34**

In the IDC demonstration, potassium permanganate was used for in situ oxidation of a DNAPL source zone consisting primarily of TCE. Lesser amounts of *cis*-1,2 DCE are also present in the aquifer at Launch Complex 34, the site of the demonstration. For the purpose of the demonstration, the relatively large source zone was divided into three test plots for three different technology applications. The 75-ft × 50-ft test plot assigned to the chemical oxidation technology is shown in Figure 3-1 and is referred to as the Oxidation Plot. The chemical oxidation and SPH™ technology demonstrations were conducted concurrently in the two outer plots, which are separated by about 80 ft. The steam injection demonstration will be conducted later.

In their final report (IT Corporation, 2000) on the IDC demonstration, the vendor has provided a detailed description of their chemical oxidation equipment, injection methodology, and process measurements. A summary description of the in situ chemical oxidation process implemented by the vendor at Launch Complex 34 follows in this section. Table 3-1 includes a chronology of events constituting the chemical oxidation demonstration. The field application of the technology was conducted over a period of 8 months from September 8, 1999 to April 17, 2000. The vendor conducted the field application relatively efficiently, without significant downtime. Because the field system did not involve any complex equipment, maintenance requirements were minimal. This period includes an unexpected interruption from September 13 to 20 due to hurricanes. Other than the hurricanes, the main interruptions were the time intervals between the three series of oxidant injections; these time intervals were used by the vendor to monitor the effectiveness of the oxidant distribution within the plot and by Battelle and the vendor to monitor the degree of interim TCE removal from the plot. The vendor used these breaks to plan each successive series of oxidant injections.

##### **3.2.1 Chemical Oxidation Equipment and Setup at Launch Complex 34**

Figure 3-2 shows a schematic of the aboveground oxidant handling system installed in and around the Oxidation Plot. Starting with solid potassium permanganate delivered to the site by Carus Chemical Company, Inc. (Carus), the vendor prepared and injected a 1.4 to 2% permanganate solution in the plot. Carus also designed and supplied a continuous mix and automated feed system for the demonstration. The feed system consisted of a portable dry bulk hopper to store and feed solid permanganate to the mixer, where hydrant water was added to make the desired injection solution. A single delivery consisted of 45,000 lb of free-flowing-grade permanganate that was transferred to the hopper by a solids blower. An auger screw conveyor transferred the permanganate from the hopper to the mixing tank. This system was automated to provide the desired flowrate



**Figure 3-1.** The Oxidation Plot and Monitoring Well Layout for Performance Assessment

and permanganate concentration, as well as to shut down if a pressure loss (pipe leak) or pressure spike (clogging) was detected in the injection lines. Figure 3-3 is a photograph of the aboveground oxidant handling system installed at Launch Complex 34.

The solution in the mixing tank was transferred to the injection well manifold using a high-pressure dual chemical feed pump. To handle the strong oxidant, the pump was made from 316 stainless steel with Teflon® seals and was rated for pumping 80 psig of water at 10 to 40 gallons per minute (gpm). Before reaching the injection manifold, the permanganate solution was passed through a 1,500-lb high-pressure sand filter to remove any particulates. Expected particulate matter in the permanganate solution included the 1% sand present in the

technical-grade potassium permanganate (to improve its flow characteristics), partially dissolved potassium permanganate, and any MnO<sub>2</sub> precipitates formed during the mixing of permanganate solids with reduced species in the hydrant water.

The vendor used polyvinyl chloride (PVC) pressure hoses with dry-disconnect quick-connect fittings to transport the oxidant solution. A grating box was placed under the premanifold and manifold piping for secondary containment in case of leaks or spills. Oxidant flow was metered to 11 individual drive stems through the injection manifold. The vendor avoided using rubber hoses, galvanized steel piping, or other materials incompatible with the strong oxidant. High-density polyethylene (HDPE) tanks, PVC pipes and hoses, stainless steel

**Table 3-1.** Chemical Oxidation Demonstration Schedule

Start Date	End Date	No. of Days	Events/Injection Stage	Volume of KMnO <sub>4</sub> solution injected (gal)	Mass of KMnO <sub>4</sub> injected (kg)	Comments
June 18, 1998			Solicitation received from IDC			Final cost proposal for design submitted by IT on 7/13/98.
August 20, 1998	Oct 20, 1998	60	Design/modeling/treatability tests			Design report submitted on 10/20/98. Cost proposal for Installation and operation submitted on 3/10/99
March 11, 1999	April 8, 1999	28	IDC approval to proceed with final design and installation			Final design/construction report submitted on 6/24/99.
August 2, 1999	Sept 5, 1999	34	Mobilization to site and setup			Tracer test performed 8/12 to 8/14. Full system mobilization 8/15 to 9/5.
April 1, 1999	June 25, 1999	90	Test Plan/QAPP			
June 21, 1999	July 17, 1999	27	Predemonstration characterization of plot			
Sept 8, 1999	Sept 27, 1999	8	First injection in Upper Sand Unit	85,793	6,059	From 9/13 through 9/20, standby for hurricane.
Sept 28, 1999	Oct 12, 1999	9	First injection in Middle Fine-Grained Unit	93,228	8,484	10/4-5 and 10/8 equipment downtime.
Oct 12, 1999	Oct 29, 1999	15	First injection in Lower Sand Unit	125,742	13,904	
			Break			Evaluate results of first injection
Nov 17, 1999	Nov 24, 1999	8	Second injection in Upper Sand Unit	65,892	4,923	
Nov 22, 1999	Nov 24, 1999	3	Second injection in Middle Fine-Grained Unit	21,591	1,348	
N/A	N/A	N/A	Second injection in Lower Sand Unit	N/A	N/A	No injection in Lower Sand Unit
			Break			Evaluate results of second injection
March 30, 2000	April 7, 2000	8	Third injection in Upper Sand Unit	43,665	3,372	
April 6, 2000	April 17, 2000	8	Third injection in Middle Fine-Grained Unit	59,421	4,589	Equipment downtime from 4/11 to 4/12
March 20, 2000	April 17, 2000	22	Third injection in Lower Sand Unit	347,653	24,277	
May 8, 2000	May 30, 2000	22	Postdemonstration characterization of plot			

appurtenances, and polyvinylidene fluoride (PVDF) or Teflon® gaskets were used. Figure 3-4 is a photograph of the oxidant injection manifold.

The vendor designed a custom injection tip (see Figure 3-5) that was used at the end of a direct-push drive rod for delivery of the oxidant to the aquifer. A separate downhole drive rod and injection tip were used at each of the 11 injection points used in Phase 1. A single direct-push rig was used to advance all 11 injection points to the first injection interval at 15 ft bgs. Oxidant was injected from all 11 points simultaneously. The rig was then used to advance each injection tip and casing 2 ft at a time, stopping at each interval to inject oxidant. The two wider-diameter sections above and below the perforated drive stem and 10-slot wire-wound screen served as packers during the injection and prevented smearing across the borehole walls, thus minimizing fouling of the

screen. A shorter screen allowed the vendor to focus injections into the desired low- or high-permeability strata encountered at different depths; longer screens would have caused the injected oxidant to preferentially enter the high-permeability strata.

### 3.2.2 Chemical Oxidation Field Operation

Before full deployment of their injection strategy, the vendor conducted a tracer test in the Oxidation Plot to evaluate the injection flowrate and radius of influence and finalize the treatment design. The tracer used was a combination of 1.4 to 2% potassium permanganate solution and 2 mg/L of pharmaceutical-grade sodium fluoride. The potassium permanganate was used as a reactive tracer to determine permanganate consumption and retardation characteristics of the aquifer; the fluoride was

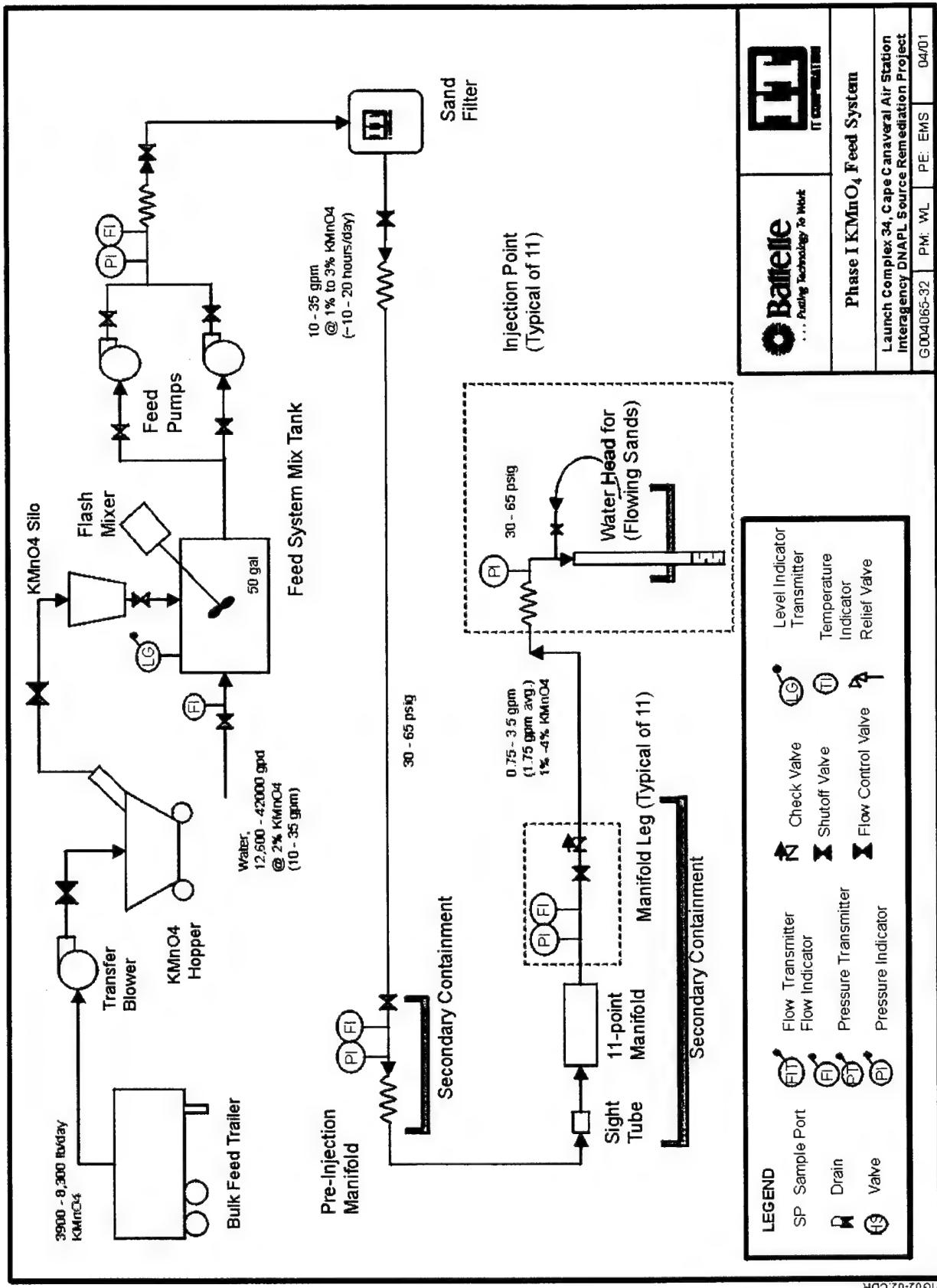
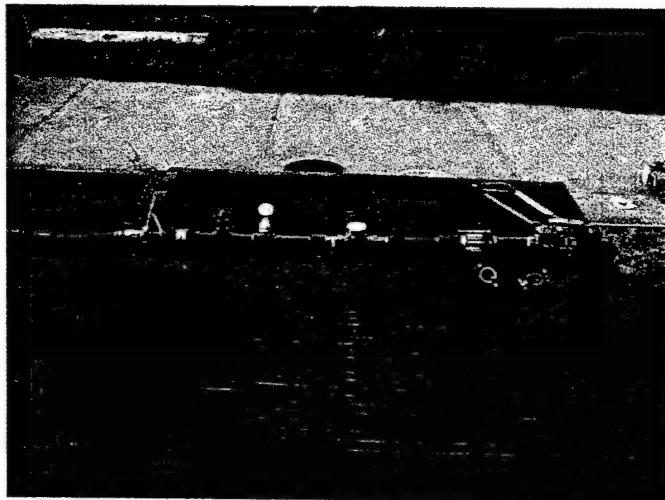


Figure 3-2. Aboveground Oxidant Handling System Installed at Launch Complex 34



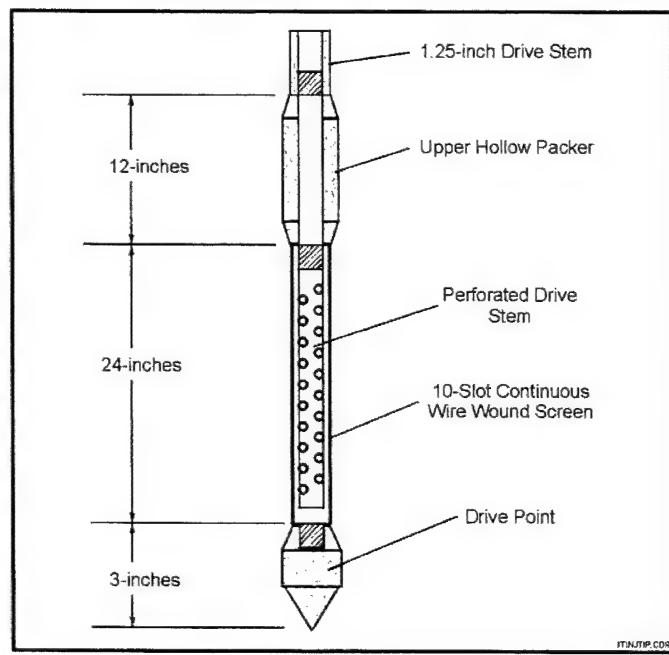
**Figure 3-3.** Chemical Oxidation Setup at Launch Complex 34 Showing Permanganate Storage Hopper and Mixer



**Figure 3-4.** Oxidant Preinjection Manifold

used as a nonreactive, nonadsorptive tracer to evaluate the radius of influence and hydraulic flow characteristics in the aquifer. The vendor gained the following important information from the tracer test:

- The sustainable injection flowrate in this aquifer ranges from 2.6 to 5.0 gpm.
- The aquifer is anisotropic with preferential flow to the north and south. Fluoride tracer was detected 26 ft north and south, but only 18 ft east and west from the injection point.



**Figure 3-5.** Schematic of the Oxidant Injection Tip Used by the Vendor  
(Source: IT Corporation, 2000)

The vendor conducted the Oxidation Plot treatment in three phases. The chronology of the oxidation field activities is given in Table 3-1. As shown in Figure 3-6, Phase 1 (first injection cycle) consisted of 11 more-or-less

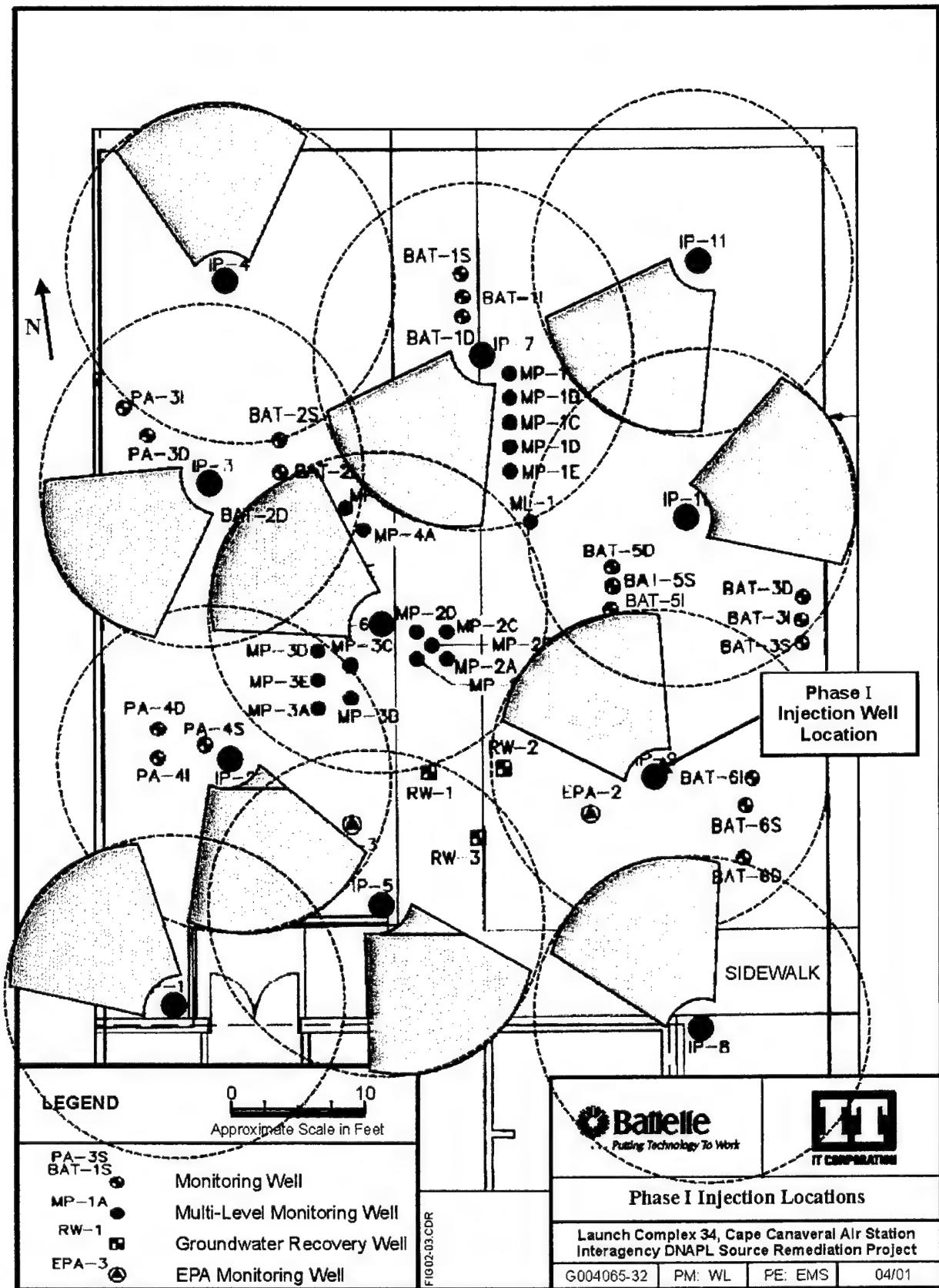


Figure 3-6. Phase 1 Injection Locations

equally spaced injection locations. At each location, the oxidant was injected serially at every 2-ft depth interval.

The amount of permanganate injected at each location and depth was based on prior knowledge of the TCE/DNAPL distribution in the plot gained from pre-demonstration characterization. The vendor injected higher amounts of permanganate at depths known to contain higher concentrations of DNAPL. The injection pressure and flowrate were used to control the radius of influence, which was also a determinant of the time period of injection at a given depth. Permanganate measurements in various multilevel wells installed throughout the plot were used to verify the radius of influence. For this purpose, the vendor installed the multilevel wells (MP-#) shown in Figure 3-6. The vendor's wells were additional to the monitoring wells (BAT-1 to BAT-5 and PA-4 clusters) installed by Battelle for independent performance assessment of the technology.

For approximately one month after Phase 1 injections, the vendor monitored the plot with a combination of groundwater and soil sampling to evaluate the effectiveness of the oxidation at different points in the plot. During this time, the vendor identified regions of the plot that appeared to have received less than the desired dose of oxidant, as indicated either by persistently higher levels of TCE or lower levels of permanganate. The distinctive discoloration of groundwater and soil exposed to different levels of permanganate was an obvious indicator of the efficiency of oxidant distribution in a given region. Phase 2 injections (second injection cycle) were directed towards regions of residual contamination in the Upper Sand Unit and Middle Fine-Grained Unit.

After another break, while the vendor monitored the plot to evaluate the effectiveness of Phase 2 injections, Phase 3 injections (third injection cycle) were conducted to polish off some more residuals in all three units — Upper Sand Unit, Middle Fine-Grained Unit, and Lower Sand Unit. During the break after Phase 2, the vendor modified the equipment and injection scheme as follows, to improve the mass throughput of oxidant into the aquifer:

- The 45,000-lb hopper was replaced by 3,300-lb "Cycle Bin" skidded containers from Carus. A forklift was rented to switch cycle bins as each bin was emptied. This change eliminated the moisture condensation and hardening of permanganate solids experienced in the larger hopper.
- To eliminate the pressure drop and fouling in the sand filter, this filter was replaced by a 21,000-gal steel "frac" tank with an epoxy liner. This tank provided flow equalization, storage, and sufficient area for settling of solids from the solution.

- An injection pump was added to convey the oxidant solution from the frac tank to the injection manifold. These changes improved the overall flow from 23 gpm to 40 gpm and increased the mass throughput of oxidant to the aquifer.
- Nine more injection tips were added to the 11 previous injection tips to obtain better coverage of the plot.
- The maximum  $\text{KMnO}_4$  concentration was reduced from 3% (the maximum allowed to fulfill regulatory requirements on trace metals) to 2% to allow better dissolution in the volume available in the mixing tank. This eliminated fouling problems due to persistence of undissolved permanganate particles.

The vendor's measurements show that injection flows varied from 0 to 5.4 gpm at individual injection locations, using injection pressures from 20 to 41 psig (IT Corporation, 2000); the flow variation was due to the variable resistance to flow in different parts of the plot. For example, the southwest corner of the plot (under the Engineering Service Building) permitted very little or no flow; this part of the plot also had the highest DNAPL mass. On the other hand, other regions of high-DNAPL mass in the plot were more conducive to flow.

The vendor estimates that hydraulic displacement from several injection points exceeded 30 ft. However, the radius of permanganate distribution around each injection point was probably less than 10 ft, and varied based on the hydraulic conductivity and TCE/organic matter content of the surrounding aquifer. Such variations were unpredictable, with instances where an injection point would permit only 0 to 0.1 gpm of flow within one horizontal foot of a point that permitted 2 to 3 gpm. Permanganate was injected for durations of up to 4 days at a given injection point. Between 8 to 20 points were injected simultaneously. Between oxidant injections, water was kept flowing through the injection tips to maintain sufficient static head to prevent fine sands and silt from fouling the tips.

During the treatment, the vendor injected a total of 842,985 gal of permanganate solution corresponding to 150,653 lb (66,956 kg) of  $\text{KMnO}_4$  mass into the Oxidation Plot aquifer (see Table 3-1). The hydrant water used for preparing the solution contained 3.8 mg/L of TOC, which adds up to 27 lb of TOC that could have consumed approximately 107 lb of permanganate (assuming a 4:1 potassium permanganate-to-TOC ratio). Approximately 22 drums or 9,300 lb of sludge was generated during the filtration of the injected liquid. After accounting for the sand (about 1,500 lb or 1% by weight of the potassium permanganate stock) that was present in the delivered

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solid potassium permanganate and some amount of MnO<sub>2</sub> generated, the vendor estimates that most of these solids were undissolved permanganate. This indicates that the mixing tank (50 gal) may have been sized too small. The permanganate supplier has indicated that one option in the future is to use sodium permanganate, which is available as a solution, instead of solid potassium permanganate.

### 3.3 Health and Safety Issues

Use of heavy equipment (hopper, GeoProbe®, mixer, pumps, and forklift) and a strong oxidant (potassium permanganate) were the main hazards encountered during the demonstration. The vendor's personnel wore Level D personal protective equipment during the demonstration. Steel-toed shoes and hard hats were worn when dealing with heavy equipment. Safety glasses were worn when dealing with the oxidant. Sometimes, operators wore Tyvek® suits when handling the oxidant injection appa-

ratus. A solution consisting of vinegar, hydrogen peroxide, and water was kept handy in a spray bottle and used for neutralizing any oxidant spills on the ground or on clothing. This solution was used whenever a hose burst or oxidant surged up into a monitoring well vault adjacent to an injection point.

The vendor reported an incidental airborne release of KMnO<sub>4</sub> while filling the silo with dry permanganate. The release abated when the hatch was sealed tighter. Fugitive dust from the cycle bin feeder in the equipment enclosure had to be abated periodically by spraying the enclosure with the neutralizing solution while wearing respiratory protection. The only incident that caused a slight concern occurred during demobilization, when the hopper used for storage of potassium permanganate solids toppled over as the permanganate supplier was dismounting it and loading it on a truck. There were no injuries during the demonstration.

## 4. Performance Assessment Methodology

Battelle, in conjunction with U.S. EPA SITE Program and Tetra Tech EM, Inc., conducted an independent performance assessment of the chemical oxidation demonstration at Launch Complex 34 (see Figure 4-1). The objectives and methodology for the performance assessment were outlined in a QAPP prepared before the field demonstration and reviewed by all stakeholders (Battelle, 1999d). The objectives of the performance assessment are:

- Estimating the TCE/DNAPL mass removal
- Evaluating changes in aquifer quality due to the treatment
- Evaluating the fate of TCE/DNAPL removed from the Oxidation Plot
- Verifying chemical oxidation operating requirements and costs.

The first objective, estimating the TCE/DNAPL mass removal percentage, is the primary objective. The rest are secondary objectives in terms of demonstration

focus and resources expended. Table 4-1 summarizes the four objectives of the performance assessment and the methodology used to achieve them.

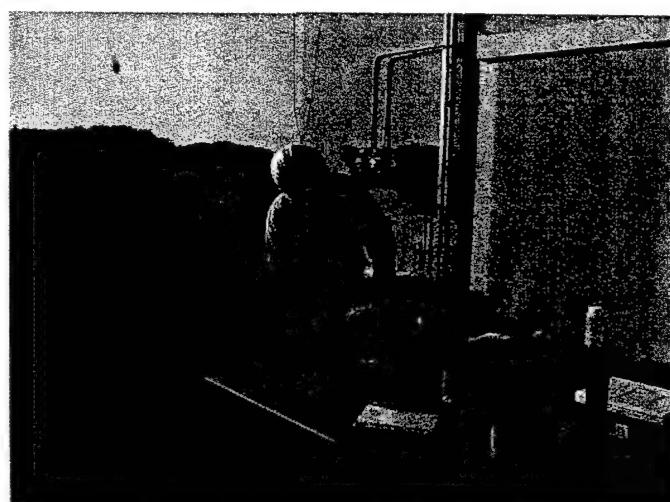
### 4.1 Estimating the TCE/DNAPL Mass Removal

The primary objective of the performance assessment is to estimate the mass removal of total TCE and DNAPL. Total TCE includes both dissolved- and free-phase TCE present in the aquifer soil matrix. DNAPL refers to free-phase TCE only and is defined by the threshold TCE concentration of 300 mg/kg described in Section 2.3. The method used for estimating TCE/DNAPL mass removal was soil sampling in the Oxidation Plot before and after the demonstration.

At the outset of the demonstration, the Technical Advisory Group proposed 90% DNAPL mass removal as a target for the three remediation technologies being demonstrated. This target represented an aggressive treatment goal for the technology vendors. Soil sampling was the method selected in the QAPP for determining percent TCE/DNAPL removal at this site. Previous soil coring, sampling, and analysis at Launch Complex 34 (Battelle, 1999b; Eddy-Dilek, 1998) had shown that this was a viable technique for identifying the boundaries of the DNAPL source zone and estimating the DNAPL mass. The advantage of soil sampling was that relatively intensive horizontal and vertical coverage of the Oxidation Plot, as well as of the dissolved-phase TCE and DNAPL distribution, could be achieved with a reasonable number of soil samples.

Although the primary focus of the performance assessment was on TCE, *cis*-1,2 DCE and vinyl chloride, contaminants that could also be oxidized by permanganate also were measured in the soil samples; however, high TCE levels often masked the other two compounds and made their detection difficult.

The statistical basis for determining the number of soil coring locations and number of soil samples required to



**Figure 4-1.** Sampling for Performance Assessment at Launch Complex 34

**Table 4-1.** Summary of Performance Assessment Objectives and Associated Measurements

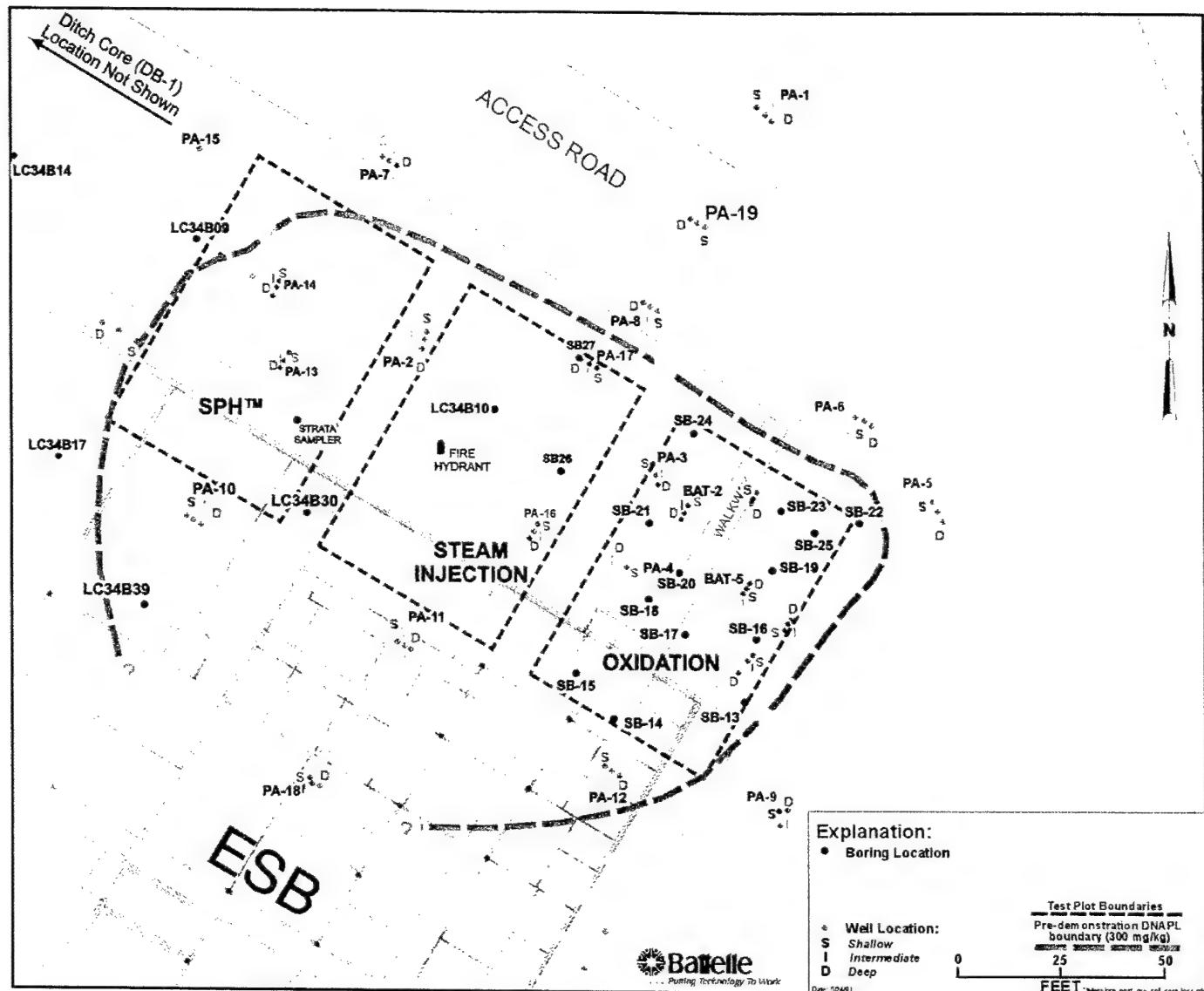
Objective	Measurements	Sampling Locations <sup>(a)</sup>
Estimating TCE/DNAPL mass removal	CVOCs in soil; before and after treatment	12 horizontal locations, every 2-ft depth interval
Evaluating changes in aquifer quality	CVOCs in groundwater; before, during, and after treatment Field parameters in groundwater; before, during, and after treatment Inorganic parameters in groundwater (cations, anions, including alkalinity); before and after treatment Trace metals in groundwater; before, during, and after treatment TOC in soil; before and after treatment TDS and BOD; before and after treatment Hydraulic conductivity; before and after treatment	Primarily well clusters BAT-2 and BAT-5; other plot wells (BAT-1, BAT-3, BAT-6, and PA-4) sampled to guide oxidant injections Primarily well clusters BAT-2 and BAT-5; perimeter wells <sup>(b)</sup> for verifying spread Primarily well clusters BAT-2 and BAT-5; perimeter wells <sup>(b)</sup> for verifying spread Primarily well clusters BAT-2 and BAT-5; perimeter wells <sup>(b)</sup> for verifying spread Two locations, three depths inside plot Primarily well clusters BAT-2 and BAT-5 BAT-5S, BAT-6S, BAT-3I, BAT-5I, BAT-6I, BAT-3D, and BAT-6D
Evaluating fate of TCE/DNAPL	Chloride in groundwater Alkalinity in groundwater Hydraulic gradients Potassium ion in groundwater Potassium permanganate in groundwater Surface emissions; primarily during oxidant injection	Primarily well clusters BAT-2 and BAT-5 in the plot; perimeter wells <sup>(b)</sup> Primarily well clusters BAT-2 and BAT-5 All wells Primarily well clusters BAT-2 and BAT-5; perimeter wells <sup>(b)</sup> Primarily well clusters BAT-2 and BAT-5; perimeter wells <sup>(b)</sup> Three locations inside plot; 3 background locations
Verify operating requirements and cost	Field observations; tracking materials consumption and costs	Field observations by vendor and Battelle; materials consumption and costs reported by vendor to MSE

(a) Monitoring well locations inside and outside the Oxidation Plot are shown in Figure 3-1. Soil coring locations are shown in Figures 4-2 (predemonstration) and 4-3 (postdemonstration).  
(b) Perimeter wells are PA-3, PA-5, PA-9, and PA-12. Distant wells PA-1, PA-8, and PA-11, as well as other wells in the vicinity were sampled for various parameters, based on ongoing data acquisition and interpretation during the demonstration.

be collected in the Oxidation Plot is described in Appendix A.1. Based on the horizontal and vertical variability observed in the TCE concentrations in soil cores collected during preliminary site characterization in February 1999, a systematic unaligned sampling approach was used to divide the plot into a 4 × 3 grid and collect one soil core in each grid cell for a total of 12 soil cores (Figure 4-2). The resulting 12 cores provided good spatial coverage of the 75-ft × 50-ft Oxidation Plot and included two cores inside the Engineering Service Building. For each soil core, the entire soil column from ground surface to aquitard was sampled and analyzed in 2-ft sections. Another set of 12 cores was similarly collected after the demonstration, as shown in Figure 4-3. Each sampling event, therefore, consisted of nearly 300 soil samples (12 cores, 23 two-foot intervals per core, plus duplicates). The line of dashes in Figures 4-2 and 4-3 represents the predemonstration DNAPL source boundary. This boundary includes all the soil coring locations where at least one of the soil samples (depth intervals) showed TCE levels above 300 mg/kg.

The soil coring, sampling, and extraction methods are described in Appendix A.2 and summarized in this section. Figures 4-4 and 4-5 show the outdoor and indoor

rigs used for soil coring outside and inside the Engineering Service Building. A direct-push rig with a 2-inch diameter, 2-ft-long sample barrel was used for coring. As soon as the sample barrel was retrieved, the 2-ft section of core was split vertically and approximately one-quarter of the core (approximately 200 g of wet soil) was deposited into a predetermined volume (250 mL) of methanol for extraction in the field. The methanol extract was transferred into 20-mL volatile organic analysis (VOA) vials, which were shipped to a certified laboratory for analysis. As compared to the more conventional method of collecting and analyzing small soil samples at discrete depths, the sampling and extraction technique used at this site provided better coverage of a heterogeneously distributed contaminant distribution. The entire vertical depth of the soil column at the coring location could be analyzed. Preliminary site characterization had showed that the vertical variability of the TCE distribution was greater than the horizontal variability, and this sampling and extraction method allowed continuous vertical coverage of the soil column. The efficiency of TCE recovery by this method (modified EPA Method 5035) was evaluated through a series of tests conducted before the demonstration (see Appendix G). In these tests, TCE was spiked into a soil core from the Launch Complex 34



**Figure 4-2.** Predemonstration Soil Coring Locations (SB-13 to SB-24) in Oxidation Plot

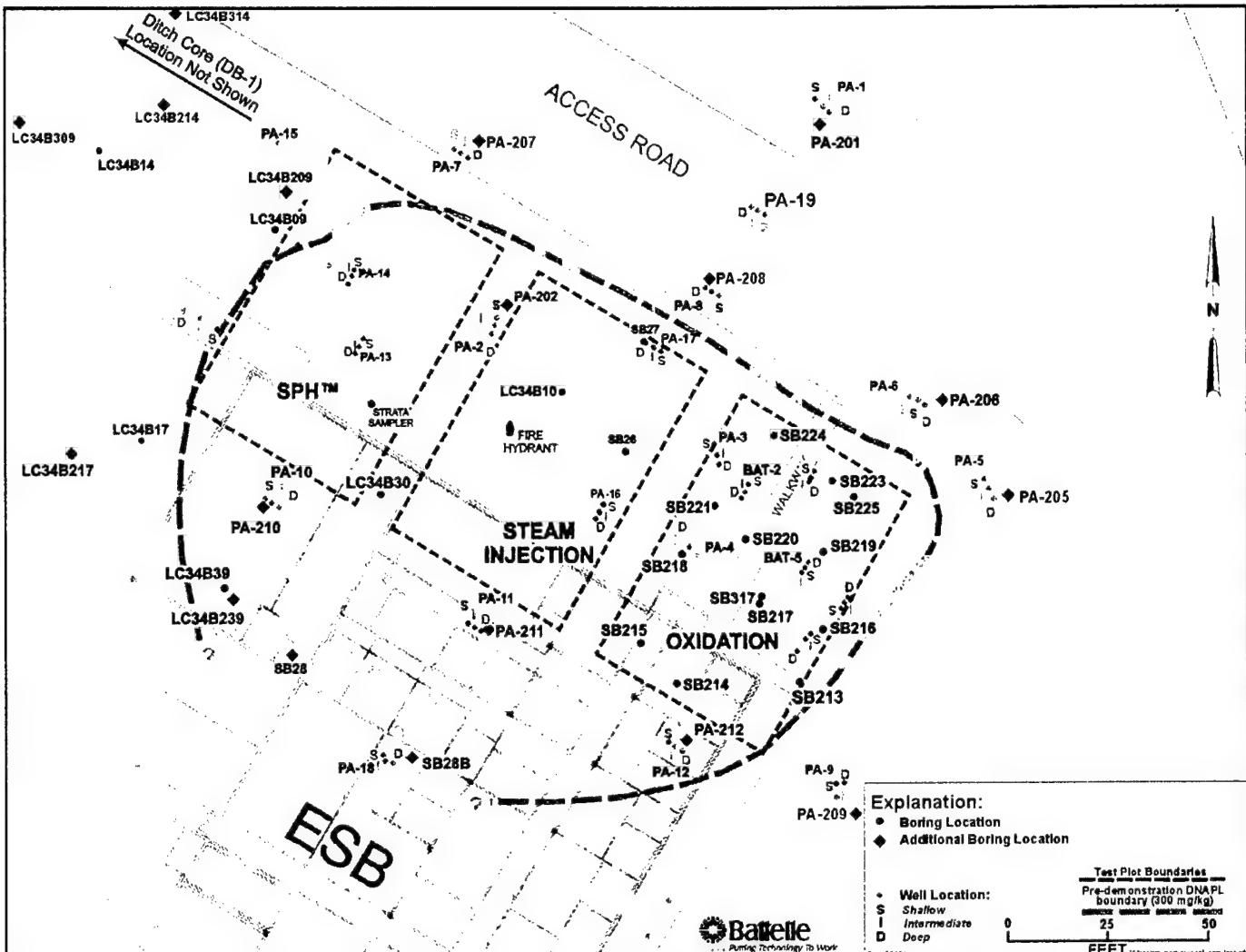
aquifer, extracted, and analyzed. Replicate extractions and analysis indicated a TCE recovery between 72 and 86%, which was considered sufficiently accurate for the demonstration.

Three data evaluation methods were used for estimating TCE/DNAPL mass removal in the Oxidation Plot:

- Contouring
- Kriging
- Pairwise comparison.

The spatial variability or spread of the TCE distribution in a DNAPL source zone typically is high, the reason being

that small pockets of residual solvent may be distributed unevenly across the source region. The three methods address this spatial variability in different ways, and therefore the resulting mass removal estimates differ slightly. Because it is impractical to sample every single point in the Oxidation Plot and obtain a true TCE mass estimate for the plot, all three methods basically address the practical difficulty of estimating the TCE concentrations at unsampled points by interpolating (estimating) between sampled points. The objective in all three methods is to use the information from a limited sample set to make an inference about the entire population (the entire plot or a stratigraphic unit).



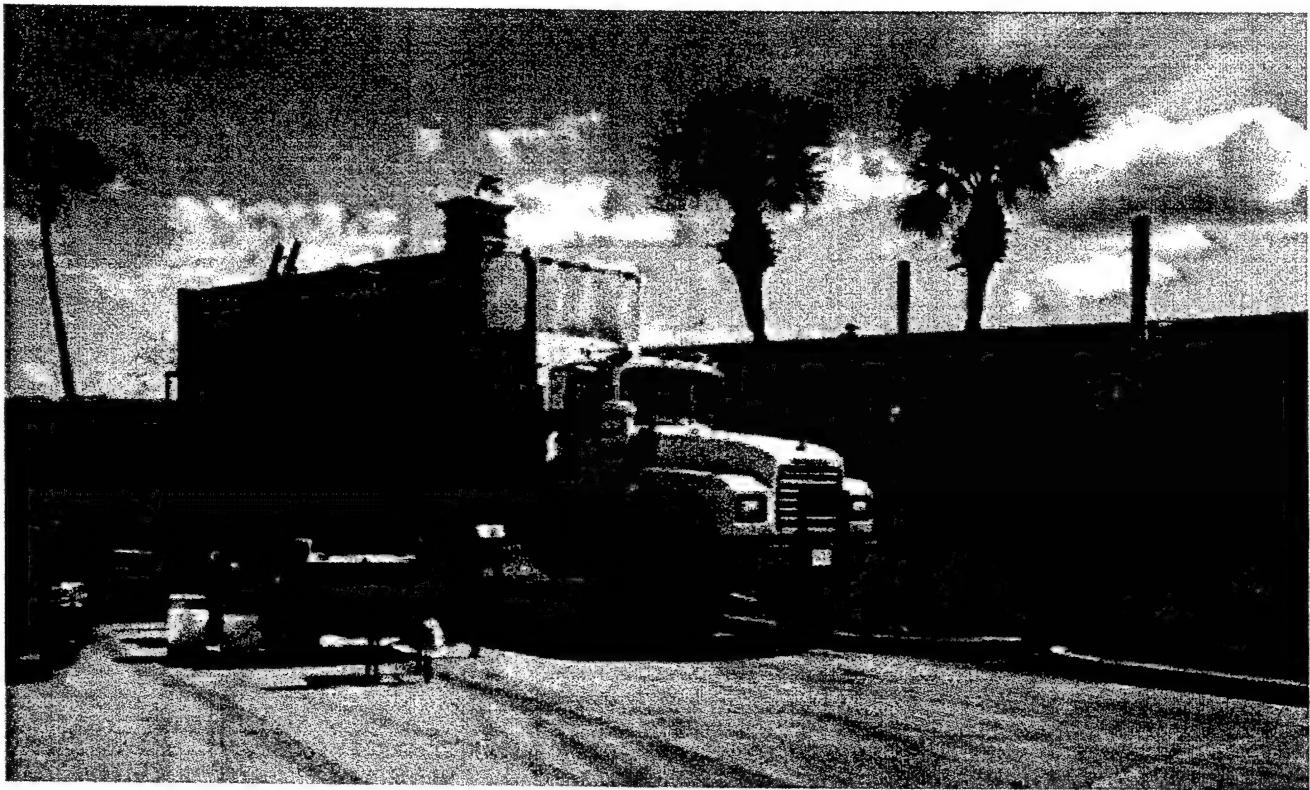
**Figure 4-3.** Postdemonstration Soil Coring Locations 9SB-213 to SB-224)

### **4.1.1 Contouring**

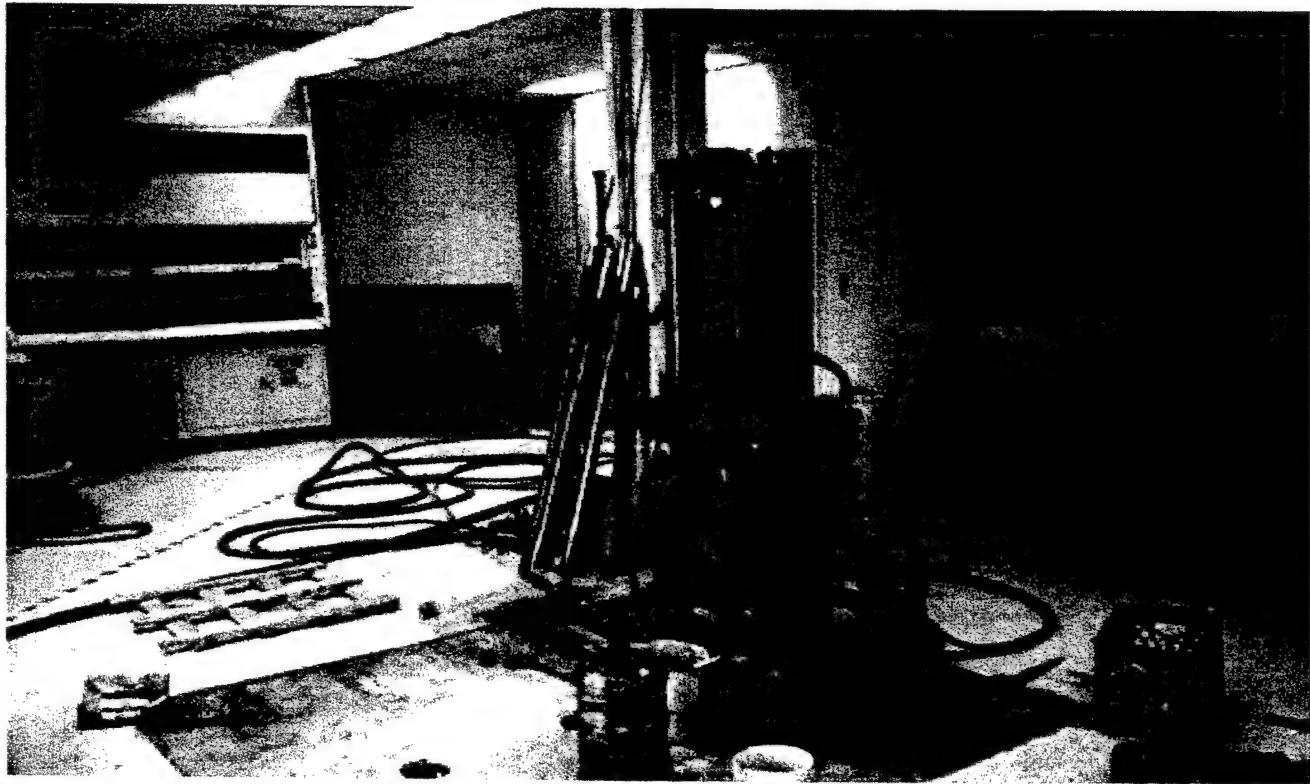
Contouring is the most straightforward and intuitive of the three methods; TCE concentrations are assumed to be linearly distributed between sampled points. A software program, such as EarthVision™, has an edge over manual calculations in that it is easier to conduct the linear interpolation in three dimensions. In contouring, the only way to address the spatial variability of the TCE distribution is to collect as large a number of samples as is practical so that good coverage of the plot is obtained; the higher the sampling density, the smaller the distances over which the data need to be interpolated. Nearly 300 soil samples were collected from the 12 coring locations in the plot during each event (predemonstration and post demonstration), which was the highest number practical for this project. Appendix A (Section A.1.1) describes how the number and distribution of

these sampling points were determined to obtain good coverage of the plot.

The contouring software EarthVision™ uses the same methodology that is used for drawing water level contour maps based on water level measurements at discrete locations in a region. The only difference with this software is that the TCE concentrations are mapped in three dimensions to generate isoconcentration shells. The TCE concentration in each shell is multiplied by the volume of the shell (as estimated by the software) and the bulk density of the soil ( $1.59 \text{ g/cm}^3$ , estimated during preliminary site characterization) to estimate a mass for each shell. The TCE mass in each region of interest (Upper Sand Unit, Middle-Fine-Grained Unit, Lower Sand Unit, and the entire plot) is obtained by adding up the portion of the shells contained in that region. The DNAPL mass is obtained by adding up the masses in only those shells



**Figure 4-4.** Outdoor Cone Penetrometer Test Rig for Soil Coring at Launch Complex 34



**Figure 4-5.** Indoor Vibra-Push Rig (LD Geoprobe® Series) Used in the Engineering Service Building

that have TCE concentrations above 300 mg/kg. Contouring provides a single mass estimate for the region of interest.

#### **4.1.2 Kriging**

Kriging is a geostatistical interpolation tool that takes the spatial correlations among the TCE data in making inferences about the TCE concentrations at unsampled points. Spatial correlation analysis determines the extent to which TCE concentrations at various points in the plot are similar or different. Generally, the degree to which TCE concentrations are similar or different is a function of distance and direction. Based on these correlations, kriging determines how the TCE concentrations at sampled points can be optimally weighted to infer the TCE concentrations/masses at unsampled points in the plot or the TCE mass in an entire region of interest (entire plot or stratigraphic unit). Kriging accounts for the uncertainty in each point estimate by calculating a standard error for the estimate. Therefore a range of TCE mass estimates is obtained instead of a single estimate; this range is defined by an average and a standard error or by a confidence interval. The confidence or level of significance required by the project objectives determines the width of this range. A level of significance of 0.2 (or 80% confidence) was determined as necessary at the beginning of the demonstration (Battelle, 1999d).

#### **4.1.3 Pairwise Comparison**

A pairwise comparison is a good way of evaluating the differences between two sample sets (pre- and post-demonstration TCE concentrations in the plot) when the (spatial) variability within each set is larger than any differences observable between the two sets. For the Oxidation Plot, the comparison between the two sample sets was conducted in terms of the ratios of the pre- and postdemonstration TCE concentrations at paired locations. These ratios were found to be normally distributed and therefore amenable to a pairwise comparison. Appendix A (Section A.1.3) contains a detailed description of the pairwise comparison approach and results.

In both contouring and kriging, the TCE mass (or range of mass estimates) in the region of interest (Upper Sand Unit, Middle-Fine-Grained Unit, Lower Sand Unit, or the entire plot) is calculated separately for the pre- and post-demonstration sampling events. The pre- and postdemonstration masses then are compared to estimate the TCE mass removal. In a pairwise comparison approach, TCE concentrations/masses are first compared at paired (matched) locations in the plot to obtain separate mass removal estimates at each location. For example, the TCE concentration at 18-20 ft bgs in the predemonstration soil core SB-16 is compared with the TCE concentration at

18-20 ft bgs in the colocated postdemonstration soil core SB-216. These individual mass removal estimates are then statistically evaluated to obtain an average and confidence interval (range) for the region of interest. The range or confidence interval for the TCE mass estimate was calculated at a significance level of 0.2 (80% confidence).

#### **4.1.4 Interpreting the Results of the Three Mass Removal Estimation Methods**

As mentioned above, the three methods address the spatial variability of the TCE distribution in different ways and, therefore, the resulting mass removal estimates differ slightly among the three methods. This section discusses the implication of these differences.

If the overall TCE mass removal efficiency of the chemical oxidation technology in the region of interest (entire plot or stratigraphic unit) is important, then contouring and kriging results are important. In both contouring and kriging, mass removal is accounted for on an absolute basis; higher mass removal in a few high-TCE concentration portions of the plot can offset low mass removal in other portions of the plot, to infer a high level of mass removal. Between contouring and kriging, kriging probably provides a more informed inference of the TCE mass removal because it takes into account the spatial correlations in the TCE distribution and the uncertainties (error) associated with the estimates. At the same time, because a large number of soil samples were collected during each event, the results in Section 5.1 show that contouring was able to overcome the spatial variability to a considerable extent and provide mass estimates that were generally within the ranges provided by kriging.

If it is important that TCE mass removal be equally efficient in different parts of the plot, then the pairwise comparison results are important. In a pairwise comparison, especially when the test statistic is stated as the ratio of the TCE concentrations (or percent TCE mass removal) at paired locations, a high level of mass removal is inferred only if mass removal is consistently high in all parts of the plot.

### **4.2 Evaluating Changes in Aquifer Quality**

A secondary objective of the performance assessment was to evaluate any short-term changes in aquifer quality due to the treatment. Chemical oxidation affects both the contaminant and the native aquifer characteristics. Pre- and postdemonstration measurements conducted to evaluate the short-term impacts of the technology application on the aquifer included:

- CVOC measurements in the groundwater inside the Oxidation Plot
- Field parameter measurements in the groundwater
- Inorganic measurements (common cations and anions) in the groundwater
- Trace metals (12 trace metals present in the industrial-grade potassium permanganate)
- TDS and biological oxygen demand (BOD)
- TOC measurements in the soil
- Hydraulic conductivity of the aquifer.

These measurements were conducted primarily in monitoring wells within the plot, but some measurements also were made in the perimeter and distant wells.

#### **4.3 Evaluating the Fate of the TCE/DNAPL Mass Removed**

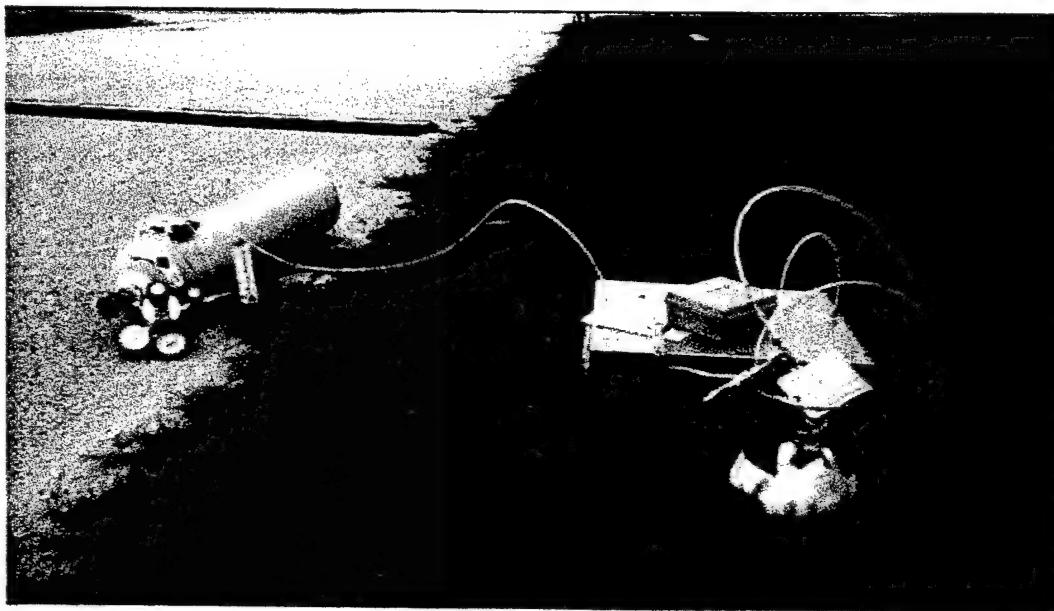
Another secondary objective was to evaluate the fate of the TCE removed from the plot by the chemical oxidation treatment. Possible pathways for the TCE removed from the plot include oxidation (destruction of TCE) and migration from the Oxidation Plot (to the surrounding regions). These pathways were evaluated by the following measurements:

- Chloride in groundwater (mineralization of CVOCs leads to formation of chloride)

- Alkalinity in groundwater (oxidation of CVOCs and native organic matter leads to formation of CO<sub>2</sub> which, in a closed system, forms carbonate)
- Hydraulic gradients (injection of oxidant solution creates gradients indicative of groundwater movement)
- Potassium ion in the Oxidation Plot and surrounding wells (potassium ion from potassium permanganate addition acts as a conservative tracer for tracking movement of injected solution)
- KMnO<sub>4</sub> in groundwater (presence of excess KMnO<sub>4</sub> indicates completeness of oxidation in the vicinity of the sample)
- Surface emission tests were conducted as described in Appendix F to evaluate the potential for CVOC losses to the vadose zone and atmosphere (see Figure 4-6).

#### **4.4 Verifying Chemical Oxidation Operating Requirements and Costs**

Another secondary objective of the demonstration was to verify the vendor's operating requirements and cost for the technology application. The vendor prepared a detailed report describing the operating requirements and costs of the chemical oxidation application (IT Corporation, 2000). An operating summary based on this report is provided in Section 3.2. Costs of the technology application also were tracked by MSE, the DOE contractor who subcontracted the chemical oxidation vendor. Site characterization costs were estimated by Battelle and Tetra Tech EM, Inc.



**Figure 4-6.** Surface Emissions Testing at Launch Complex 34

## 5. Performance Assessment Results and Conclusions

The results of the performance assessment methodology outlined in Section 4 are described in this section.

### 5.1 TCE/DNAPL Mass Removal

Section 4.1 describes the methodology used to estimate the masses of total TCE and DNAPL removed from the plot due to the chemical oxidation application at Launch Complex 34. Intensive soil sampling was the primary tool for estimating total TCE and DNAPL mass removal. Total TCE refers to both dissolved-phase and DNAPL TCE. DNAPL refers to that portion of total TCE in a soil sample that exceeds the threshold concentration of 300 mg/kg (see Section 2.3). Pre- and postdemonstration concentrations of TCE at 12 soil coring locations (nearly 300 soil samples) inside the Oxidation Plot were tabulated and graphed to *qualitatively* identify changes in TCE/DNAPL mass distribution and efficiency of the chemical oxidation application in different parts of the plot (Section 5.1.1). In addition, TCE/DNAPL mass removal was *quantified* by three methods:

- Contouring (Section 5.1.2)
- Kriging (Section 5.1.3)
- Pairwise comparison (Section 5.1.4).

These quantitative techniques for estimating TCE/DNAPL mass removal due to the chemical oxidation application are described in Section 4.1; the results are described in Sections 5.1.2 through 5.1.4.

#### 5.1.1 Qualitative Evaluation of Changes in TCE/DNAPL Distribution

Figure 5-1 charts the pre- and postdemonstration concentrations of TCE in the soil samples from the 12 coring locations in the Oxidation Plot. This chart allows a simple numerical comparison of the pre- and postdemonstration TCE concentrations at paired locations. The colors in the chart are indicative of the color observed in each soil sample at 2-ft intervals. The gray and tan colors are the natural colors of the Launch Complex 34 soil. The orange color indicates the creation of mildly oxidizing conditions,

when the first trace of oxidant reaches the soil and native iron precipitates out as ferric compounds. The brown color probably indicates moderately oxidizing conditions where MnO<sub>2</sub>, a byproduct of TCE and native organic matter oxidation, has formed. The purple color indicates an excess of permanganate.

These visual indicators were not always representative of the level of TCE oxidation/removal observed in the corresponding soil samples. However, the colors did provide guidance on the efficiency of the oxidant distribution at different points in the plot. Based on the colors, oxidant distribution appeared to be best in the Upper Sand Unit, followed by the Lower Sand Unit. The Middle Fine-Grained Unit showed less penetration of the oxidant than the other two stratigraphic units. Based on the pervasiveness of purple color, the soil core SB220 in the center of the plot showed the best oxidant distribution at all depths. The predominance of native colors indicated that the soil core SB215 located under the Engineering Service Building sustained less penetration of oxidant than other parts of the plot. In general, underground access and local geologic heterogeneities appear to have played a considerable role in the efficiency of oxidant distribution.

The chart in Figure 5-1 shows that at several locations in the plot, TCE concentrations were reduced considerably in all three units. The thicker horizontal lines in the chart indicate the depths at which the Middle Fine-Grained Unit was encountered at each location. As seen in Figure 5-1, the highest predemonstration contamination detected was 30,056 mg/kg of TCE in SB14, the soil core located under the Engineering Service Building along the southern edge of the plot, where the contamination was the highest. This hot spot was present at the interface between the Middle Fine-Grained Unit and the Lower Sand Unit; concentrations in the vicinity of this hot spot were reduced considerably by the chemical oxidation application, as seen in the postdemonstration core SB214. The highest postdemonstration TCE concentration was 9,727 mg/kg, found in soil core SB215. This high residual contamination was present in the Middle

Top Depth	Bottom Depth	Pre-Demo SB13		Post-Demo SB213		Pre-Demo SB16		Post-Demo SB216		Pre-Demo SB19		Post-Demo SB219		Pre-Demo SB25		Post-Demo SB225	
		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
0	2	0.4	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2	4	0.2	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
4	6	0.2	2.3	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
6	8	0.4	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
8	10	0.5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
10	12	0.5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
12	14	0.4	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
14	16	0.8	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
16	18	0.5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
18	20	21.9	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
20	22	105.9	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
22	24	234.6	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
24	26	304.2	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
26	28	318.4	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
28	30	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
30	32	66.8	7.1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
32	34	23.4	2.8	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
34	36	7.3	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
36	38	13.2	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
38	40	19.9	2.2	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
40	42	68.57	5.7	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
42	44	44	4.0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
44	46	18.05	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

Figure 5-1. Distribution of Pre- and Postdemonstration TCE Concentrations (mg/kg) in the Oxidation Plot Soil (page 1 of 3)

Top Depth	Bottom Depth	Pre-Demo SB14	Post-Demo SB214	Pre-Demo SB17	Post-Demo SB217	Pre-Demo SB317	Post-Demo SB317	Post-Demo SB20		Post-Demo SB220		Post-Demo SB223	
								ND	ND	ND	ND	ND	ND
0	2	0.2	ND	0.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
2	4	0.3	ND	0.3	ND	ND	ND	ND	ND	ND	ND	ND	ND
4	6	0.2	ND	0.4	ND	ND	ND	ND	ND	ND	ND	ND	ND
6	8	0.3	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
8	10	0.3	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
10	12	0.5	3.7	ND	12.9	ND	ND	ND	ND	ND	ND	ND	39.9
12	14	1.6	ND	0.4	ND	ND	ND	ND	ND	ND	ND	ND	44.8
14	16	0.4	ND	1.2	ND	ND	ND	ND	ND	ND	ND	ND	ND
16	18	3.8	ND	0.4	ND	ND	ND	ND	ND	ND	ND	ND	ND
18	20	28.5	ND	14.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
20	22	114.3	ND	46.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
22	24	236.0	ND	4,412.4	0.6	ND	ND	ND	ND	ND	ND	ND	ND
24	26	225.8	ND	215.1	1.8	ND	ND	ND	ND	ND	ND	ND	ND
26	28	3,798.4	ND	210.5	17.6	ND	ND	ND	ND	ND	ND	ND	ND
28	30	446.6	NA	339.8	36.1	ND	ND	ND	ND	ND	ND	ND	ND
30	32	2,261.2	31.2	360.5	6.8	ND	ND	ND	ND	ND	ND	ND	ND
32	34	30,056.1	288.3	191.4	1.1	ND	ND	ND	ND	ND	ND	ND	ND
34	36	8,856.9	1,201.7	215.2	0.5	ND	ND	ND	ND	ND	ND	ND	ND
36	38	15,113.3	97.5	258.7	20.7	ND	ND	ND	ND	ND	ND	ND	ND
38	40	853.3	832.0	188.2	134.5	ND	ND	ND	ND	ND	ND	ND	ND
40	42	NA	330.3	156.5	32.5	ND	ND	ND	ND	ND	ND	ND	ND
42	44	1,264.3	555	138.0	6.5	ND	ND	ND	ND	ND	ND	ND	ND
44	46	189.3	211.4	215.4	ND	ND	ND	ND	ND	ND	ND	ND	ND
						857.6	8,349.8	10.8	NA	NA	NA	NA	NA

Figure 5-1. Distribution of Pre- and Postdemonstration TCE Concentrations (mg/kg) in the Oxidation Plot Soil (page 2 of 3)

<b>Top Depth</b>	<b>Bottom Depth</b>	<b>Pre-Demo SB15</b>	<b>Post-Demo SB215</b>	<b>Pre-Demo SB18</b>	<b>Post-Demo SB218</b>	<b>Pre-Demo SB21</b>	<b>Post-Demo SB221</b>	<b>Pre-Demo SB24</b>	<b>Post-Demo SB224</b>
0	2	ND	0.4	ND	ND	ND	ND	ND	ND
2	4	0.2	0.4	0.2	ND	0.7	ND	ND	ND
4	6	0.4	0.9	0.8	ND	0.2	ND	ND	ND
6	8	0.4	ND	0.6	ND	ND	2.2	ND	ND
8	10	0.8	1.0	0.8	ND	0.4	ND	ND	ND
10	12	1.6	0.5	0.5	ND	0.4	ND	ND	ND
12	14	1.8	ND	0.4	ND	0.7	ND	ND	ND
14	16	0.6	ND	0.2	ND	0.6	ND	ND	ND
16	18	1.2	39.3	5.9	ND	1.1	ND	5	ND
18	20	1.3	83.6	35.1	ND	3.4	ND	10.0	ND
20	22	2.1	6.2	1.10	ND	5.1	ND	34.3	ND
22	24	2.5	NA	3,699.8	ND	72.9	ND	57.3	ND
24	26	3.0	2,261.9	6,898.9	3.6	65.1	3.7	59.3	ND
26	28	3.2	9,726.8	1,416.2	ND	226.2	44.7	191.6	198.4
28	30	7,029.5	3390.9	441.9	ND	NA	69.4	137.3	4,200.9
30	32	4,901.0	3,391.8	586.8	NA	189.0	201.2	84.8	220.2
32	34	6.6	3,722.9	321.9	ND	97.9	3.5	62.3	297.3
34	36	NA	3,279.6	1,767.3	NA	7,881.2	1,093.5	154.7	105.8
36	38	17,686.5	4,132.9	3,201.6	ND	7,391.4	409.5	439.7	278.2
38	40	1,322.8	8,313.7	8,374.1	ND	7,397.8	1,256.5	101.7	124.7
40	42	2,750.7	8,494.6	778.2	ND	5,913.0	65.3	43.0	583.1
42	44	4,834.1	NA	3,546.6	ND	10,156.7	4.3	13.3	NA
44	46	6.6	9.0	NA	NA	NA	NA	NA	NA

NA: Not available.

ND: Not detected.

Solid horizontal lines demarcate MFGU.

**Figure 5-1.** Distribution of Pre- and Postdemonstration TCE Concentrations (mg/kg) in the Oxidation Plot Soil (page 3 of 3)

Fine-Grained Unit at a location under the building, probably the region that presented the most geologic and operational difficulty for oxidation treatment through injection points outside the building.

Figures 5-2 to 5-4 show representative pre- and post-demonstration distributions of TCE in soil from the Upper Sand Unit, Middle Fine-Grained Unit, and Lower Sand Unit in the Oxidation Plot and surrounding aquifer. A graphical representation of the TCE data illustrates the areal and vertical extent of the oxidant distribution and the changes in TCE concentrations. The colors yellow to red indicate DNAPL (TCE >300 mg/kg). In general, the portions of the aquifer under the building (SB14 and SB15) and along the western boundary of the plot (SB18 and SB21) had the highest predemonstration contamination, especially in the Middle Fine-Grained Unit and Lower Sand Unit. The postdemonstration coring showed that the chemical oxidation process had caused a considerable decline in TCE concentrations throughout the Oxidation Plot. Postdemonstration soil cores SB218 and SB221, along the western edge of the plot, showed the sharpest declines in TCE/DNAPL concentrations. On the other hand, cores SB214 and SB215, collected under the building, contained considerable postdemonstration concentrations of both total TCE and DNAPL. This indicates that oxidant distribution under the building was not as efficient as in the rest of the plot.

Figures 5-5 to 5-7 show the distribution of potassium permanganate in the shallow, intermediate, and deep wells in the Launch Complex 34 aquifer, as measured by spectrophotometry in May 2000, soon after the end of the oxidant injection process. The permanganate levels in the monitoring wells are probably a measure of the excess oxidant in the aquifer; that is, the permanganate left over after the TCE and native organic matter in the vicinity had been oxidized. These figures show that some excess potassium permanganate was present in most parts of the Oxidation Plot and surrounding aquifer, although some regions seemed to have received a higher oxidant dose than others. Monitoring wells BAT-5S and BAT-5D seemed to have barely measurable levels of permanganate, indicating that preferential pathways may have guided the oxidant flow away from this region. In fact, BAT-5S was the only well in the Oxidation Plot that showed an increase in TCE concentration throughout the demonstration (see Section 5.2.1).

## **5.1.2 TCE/DNAPL Mass Removal Estimation by Contouring**

Section 4.1.1 describes the use of contouring to estimate pre- and postdemonstration TCE/DNAPL masses and calculate TCE/DNAPL mass removal. In this method,

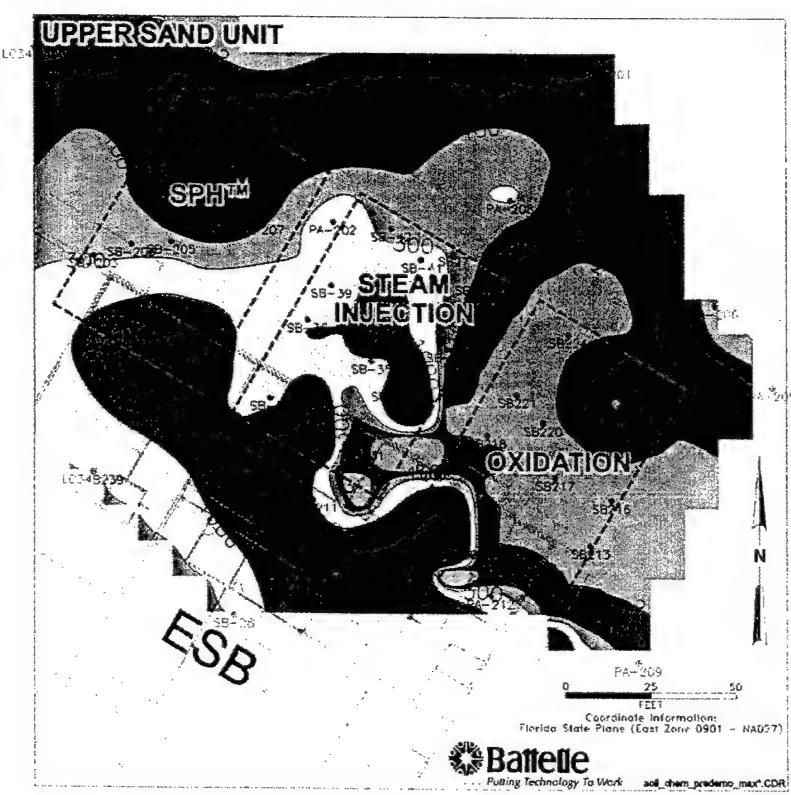
EarthVision™, a three-dimensional contouring software, is used to group the TCE concentration distribution in the Oxidation Plot into three-dimensional shells (or bands) of equal concentration. The concentration in each shell is multiplied by the volume of the shell and the bulk density of the soil to arrive at the TCE mass in that shell. The masses in the individual shells are added up to arrive at a TCE mass for the entire plot; this process is conducted separately for the pre- and postdemonstration TCE distributions in the Oxidation Plot. The predemonstration TCE/DNAPL mass in the entire plot then can be compared with the postdemonstration mass in the entire plot to estimate TCE/DNAPL removal. The results of this evaluation are described in this section.

Table 5-1 presents the estimated masses of total TCE and DNAPL in the Oxidation Plot and the three individual stratigraphic units. Under predemonstration conditions, soil sampling indicated the presence of 6,122 kg of total TCE (dissolved and free phase), approximately 5,039 kg of which was DNAPL. Following the demonstration, soil sampling indicated that 1,100 kg of total TCE remained in the plot; approximately 810 kg of this remnant TCE was DNAPL. Based on these estimates, 5,022 kg of total TCE, including 4,229 kg of DNAPL, was removed from the plot. Therefore, the overall mass removal effected by the chemical oxidation process was 82% of total TCE and 84% of DNAPL.

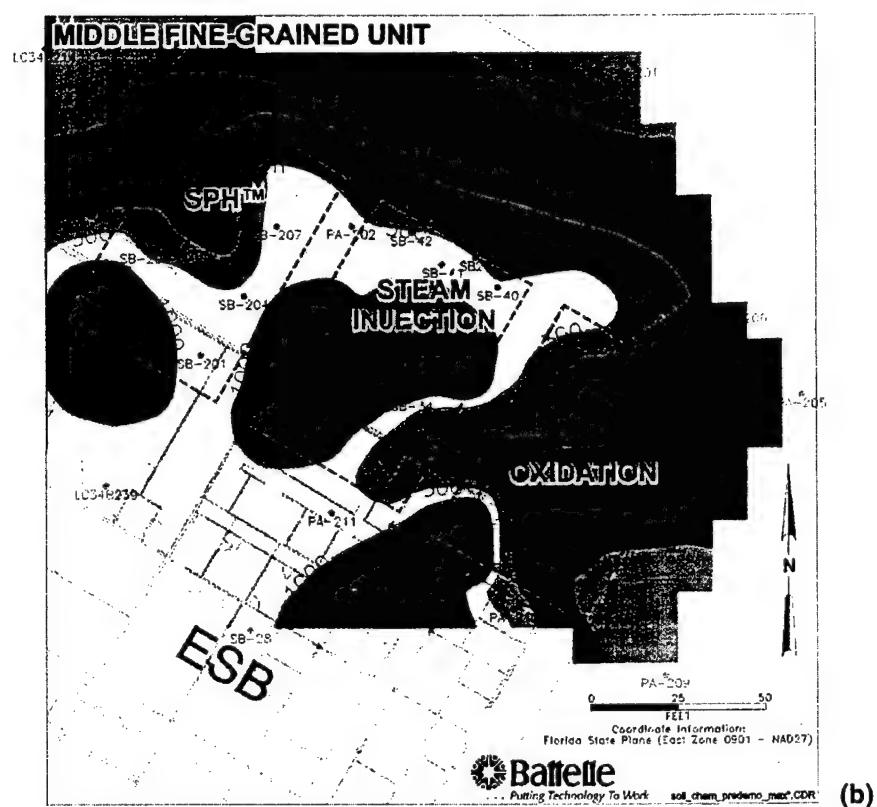
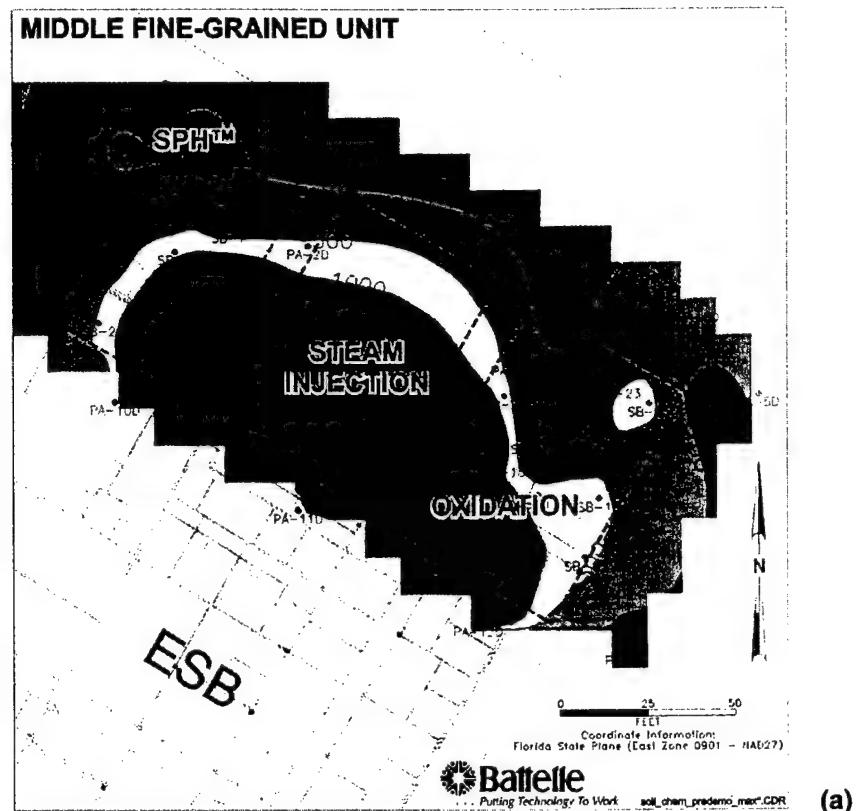
Table 5-1 indicates that the highest mass removal (97% of total TCE and 98% of DNAPL) was achieved in the Upper Sand Unit, followed by the Lower Sand Unit. Substantial TCE/DNAPL mass was removed in the Middle Fine-Grained Unit as well, but the removal efficiency in this finer-grained unit was not as high as in the two sandy units.

## **5.1.3 TCE Mass Removal Estimation by Kriging**

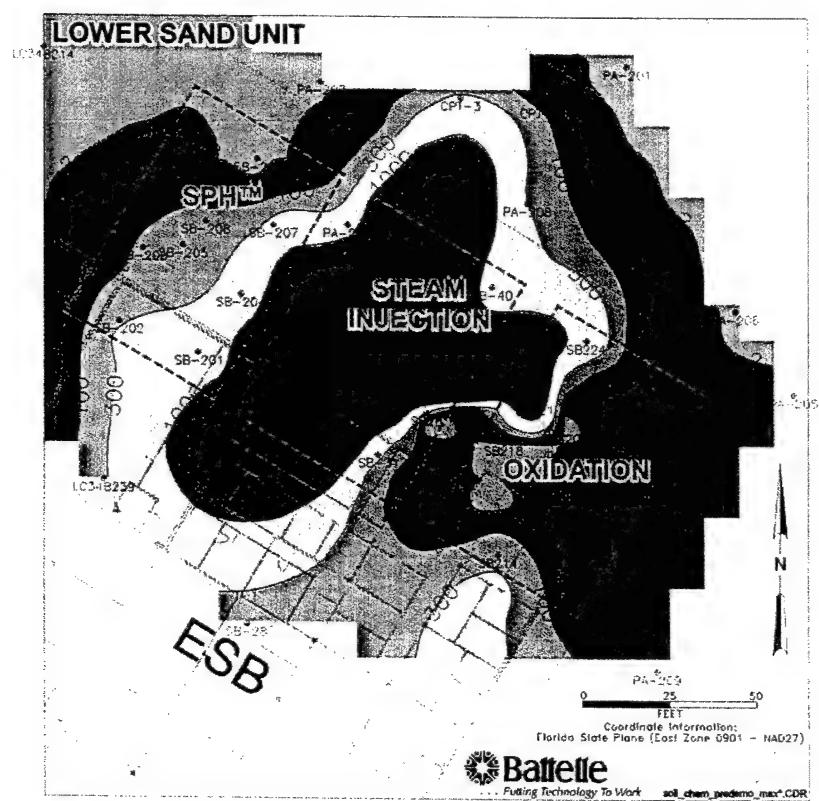
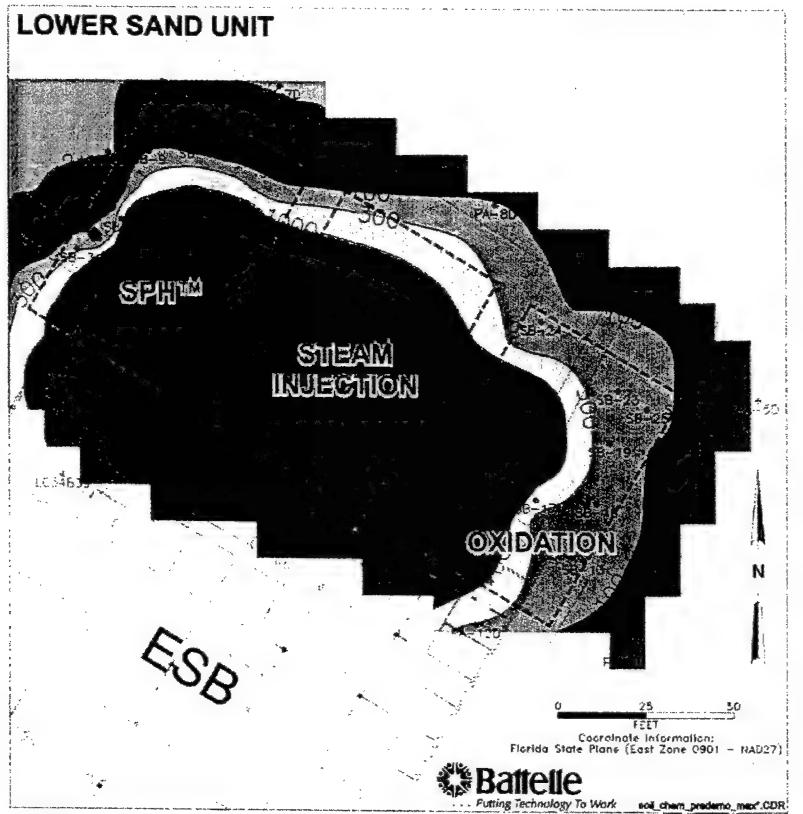
Section 4.1.2 describes the use of kriging to estimate the pre- and postdemonstration TCE masses in the aquifer. Whereas the contouring method linearly interpolates the TCE measurements at discrete sampling points to estimate TCE concentrations at unsampled points in the plot, kriging takes into account the spatial variability and uncertainty of the TCE distribution when estimating TCE concentrations (or masses) at unsampled points. Consequently, kriging provides a range of probable values rather than single TCE concentration estimates. Kriging is a good way of obtaining a global estimate (estimate for one of the three stratigraphic units or the entire plot) for the parameters of interest (such as pre- and post-demonstration TCE masses), when the parameter is heterogeneously distributed.



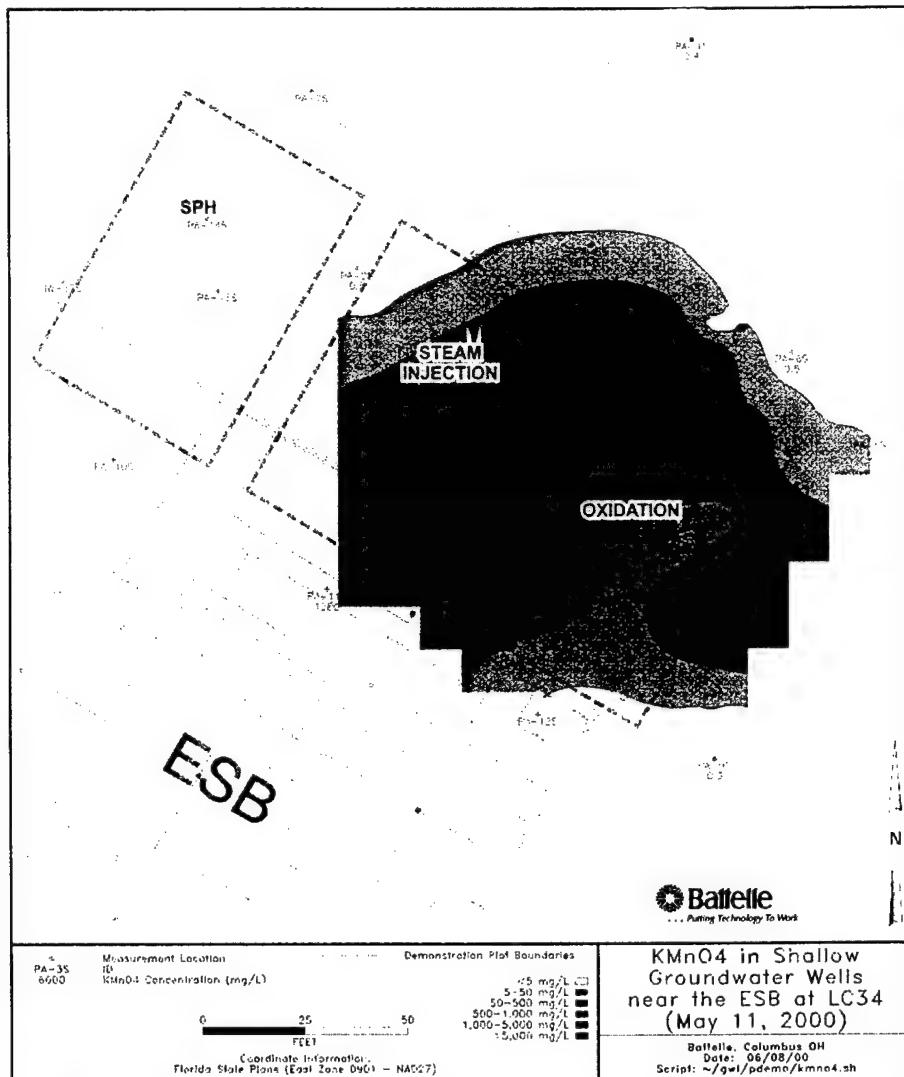
**Figure 5-2.** Representative Predemonstration (a) and Postdemonstration (b) Concentrations of TCE (mg/kg) in the Upper Sand Unit



**Figure 5-3.** Representative Predemonstration (a) and Postdemonstration (b) Concentrations of TCE (mg/kg) in the Middle Fine-Grained Unit



**Figure 5-4.** Representative Predemonstration (a) and Postdemonstration (b) Concentrations of TCE (mg/kg) in the Lower Sand Unit

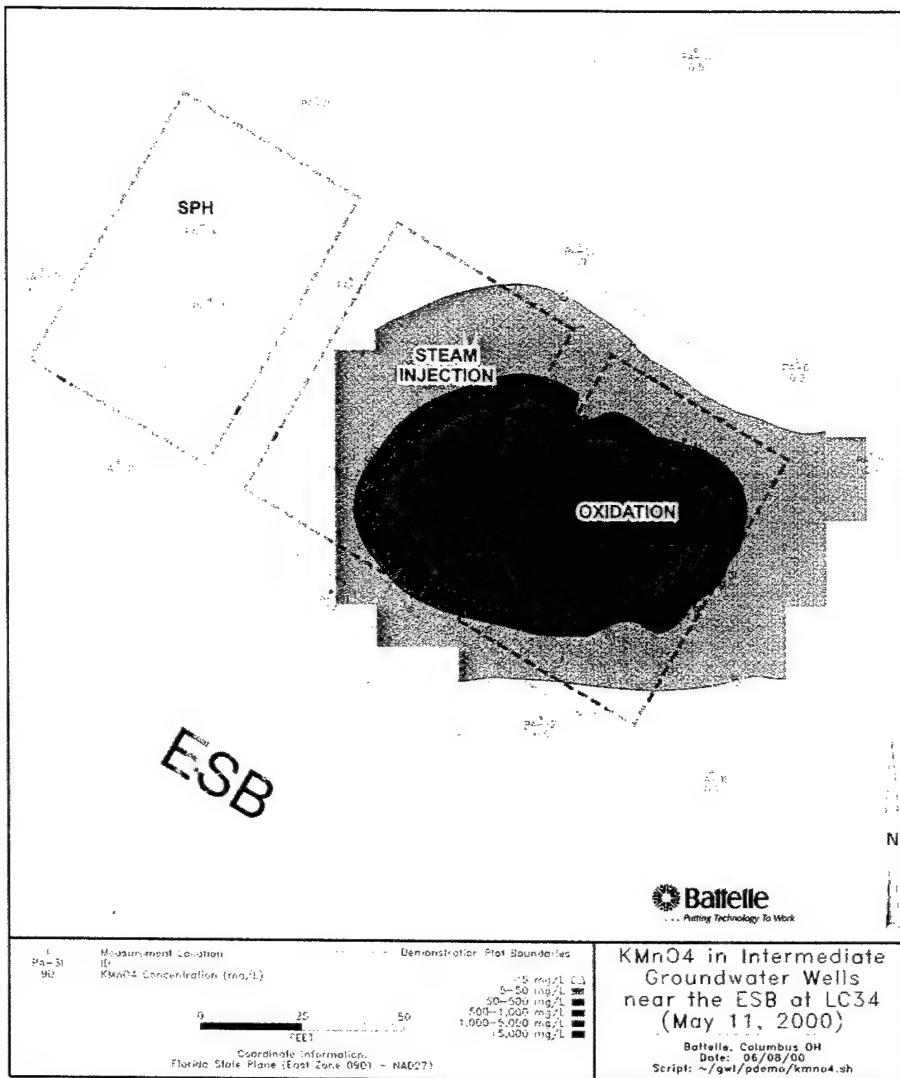


**Figure 5-5.** Distribution of Potassium Permanganate ( $KMnO_4$ ) in Shallow Wells near the Engineering Service Building at Launch Complex 34 (May 2000)

Appendix A.1.1 contains a description of the application and results of kriging the TCE distribution in the Oxidation Plot. Table 5-2 summarizes the total TCE mass estimates obtained from kriging. This table contains an average and range for each global estimate (Upper Sand Unit, Middle Fine-Grained Unit, Lower Sand Unit, and the entire plot total). Limiting the evaluation to DNAPL instead of total TCE limits the number of usable data points to those with TCE concentrations greater than 300 mg/kg. To avoid using too small a number of data points (especially for the postdemonstration DNAPL mass estimates), kriging was conducted on total TCE values only.

The pre- and postdemonstration total TCE masses estimated from kriging match the total TCE obtained from contouring relatively well, probably because the high sampling density (almost 300 soil samples in the plot per

event) allows contouring to capture much of the variability of the TCE distribution in the plot. Kriging shows that between 62 and 84% (75% on average) of the pre-demonstration TCE mass was removed from the plot due to the chemical oxidation application. TCE mass removal was highest in the Upper Sand Unit, followed by the Lower Sand Unit. TCE mass removal was lowest in the Middle Fine-Grained Unit. An interesting observation from Table 5-2 is that the estimated ranges for the pre- and postdemonstration TCE masses do not overlap, either for the entire plot or for any of the three stratigraphic units; this indicates that the mass removal due to the chemical oxidation application is significant at the 80% confidence level. At least 62% of the predemonstration TCE mass can be said to have been removed from the plot due to the chemical oxidation application. The initial 90% DNAPL removal goal set for the demonstration



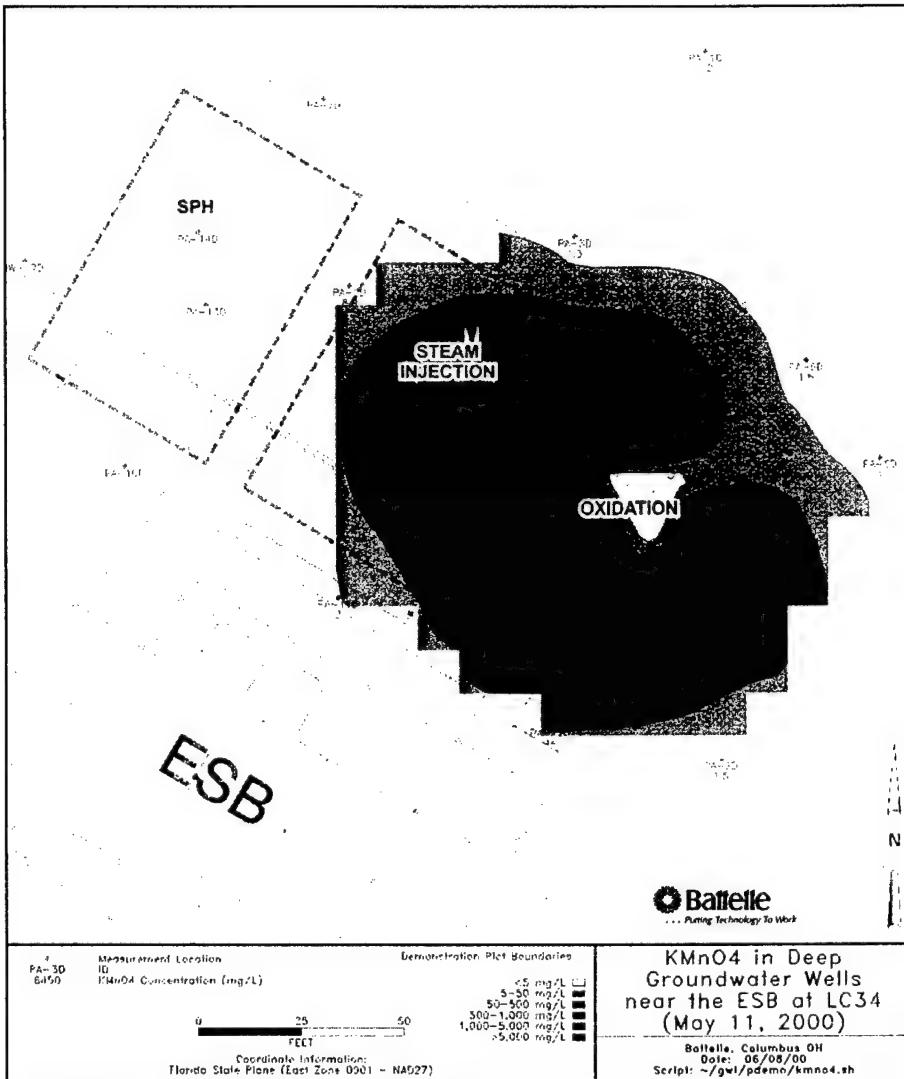
**Figure 5-6.** Distribution of Potassium Permanganate (KMnO<sub>4</sub>) in Intermediate Wells near the Engineering Service Building at Launch Complex 34 (May 2000)

was probably not met due to the limited access to the DNAPL under the building and the limited distribution of oxidant in the Middle Fine-Grained Unit.

#### 5.1.4 TCE/DNAPL Mass Removal Evaluation by Pairwise Comparison

Section 4.1.3 describes the pairwise comparison method for evaluating TCE/DNAPL mass removal efficiency in the three stratigraphic units and the entire plot. In this method, mass removal is calculated separately at each paired sampling location and then averaged. Therefore, the mass removal efficiency in the entire plot (or stratigraphic unit) is an average of the removal efficiencies or percent mass removal estimates at individual sampling locations. Table 5-3 presents the mass removal efficiency indicated by the pairwise comparison method.

The overall mass removal efficiency from the Oxidation Plot estimated from a pairwise comparison was between 49 and 100% (77% on average) for total TCE and between 58 and 100% (83% on average) for DNAPL. The confidence interval is based on a level of significance of 0.2 (80% confidence). The pairwise comparison stresses mass removal efficiencies at individual points, regardless of their contribution to the global estimate for the entire plot or an entire stratigraphic unit. For example, in a pairwise comparison, a reduction in TCE concentration at Point A from 2,000 mg/kg to 1,000 mg/kg (50% removal) is accounted for in the same way as a reduction at Point B from 2 to 1 mg/kg (50% removal). The confidence intervals are wider for the individual stratigraphic units than for the entire plot because estimates for the individual units are based on a smaller number of samples.



**Figure 5-7.** Distribution of Potassium Permanganate (KMnO<sub>4</sub>) in Deep Wells near the Engineering Service Building at Launch Complex 34 (May 2000)

The mass removal estimates obtained in the Oxidation Plot by the three methods are consistent. Consistent with contouring and kriging, pairwise comparison also shows that the highest removal efficiency was achieved in the Upper Sand Unit. Confidence intervals were not

calculated for DNAPL removal from the individual units because an even smaller subset of samples (only those samples with TCE greater than 300 mg/kg) would be involved.

**Table 5-1.** Estimated Total TCE and DNAPL Mass Removal by Contouring the TCE Distribution in Soil

Stratigraphic Unit	Total TCE Mass (kg)		DNAPL Mass (kg)		Change In Mass	
	Predemonstration	Postdemonstration	Predemonstration	Postdemonstration	Total TCE	DNAPL
Upper Sand Unit	846	23	601	10	-97%	-98%
Middle Fine-Grained Unit	1,048	233	749	163	-78%	-78%
Lower Sand Unit	4,228	844	3,689	637	-80%	-83%
Total (Entire Plot)	<b>6,122</b>	<b>1,100</b>	<b>5,039</b>	<b>810</b>	<b>-82%</b>	<b>-84%</b>

**Table 5-2.** Estimated Total TCE Mass Removal by Kriging the TCE Distribution in Soil

Stratigraphic Unit	Predemonstration Total TCE Mass (kg)		Postdemonstration Total TCE Mass (kg)		Change	
	Average	80% Confidence Interval	Average	80% Confidence Interval	Average	80% Confidence Interval
Upper Sand Unit	454	250 to 659	26	18 to 34	-94%	-87 to -97%
Middle Fine-Grained Unit	2,836	1,668 to 4,005	872	532 to 1,211	-69%	-27 to -87%
Lower Sand Unit	4,408	3,519 to 5,298	1,030	788 to 1,272	-77%	-64 to -85%
Total (Entire Plot)	7,699	6,217 to 9,182	1,928	1,511 to 2,345	-75%	-62 to -84%

**Table 5-3.** Estimated Total TCE and DNAPL Mass Removal by Pairwise Comparison of TCE Concentrations in Soil

Stratigraphic Unit	Change in Total TCE Mass			Change in DNAPL Mass	
	Average	80% Confidence Interval	Average	80% Confidence Interval	
Upper Sand Unit	-94%	-38 to -100%	NA <sup>(a)</sup>	NA	
Middle Fine-Grained Unit	-78%	-21 to -100%	NA	NA	
Lower Sand Unit	-77%	-51 to -100%	NA	NA	
Total (Entire Plot)	-77%	-49 to -100%	-83%	-58 to -100%	

(a) NA = not applicable. Insufficient number of data points with TCE concentrations greater than the DNAPL threshold of 300 mg/kg prevented statistical pairwise comparison in individual stratigraphic units. Enough data points were available for evaluating entire plot.

### 5.1.5 TCE/DNAPL Mass Removal Summary

In summary, the evaluation of TCE concentrations in soil indicates the following:

- In the horizontal plane, the highest predemonstration DNAPL contamination was under the Engineering Service Building and along the western boundary of the Oxidation Plot.
- In the vertical plane, the highest predemonstration DNAPL contamination was associated with the Lower Sand Unit.
- A statistical evaluation (kriging) of the pre- and postdemonstration TCE concentrations in soil shows that between 62 and 84% of the estimated predemonstration total TCE mass in the Oxidation Plot was removed due to the chemical oxidation application. Total TCE includes both dissolved-phase TCE and DNAPL.
- Contouring of the pre- and postdemonstration TCE/DNAPL soil concentrations shows that approximately 84% of the estimated predemonstration DNAPL mass in the Oxidation Plot was removed due to the chemical oxidation application.
- Oxidant was injected at relatively high pressures at several locations and depths within the Oxidation Plot and this improved the overall

TCE/DNAPL mass removal. However, despite the high injection pressures and spatially intensive injection scheme, localized aquifer heterogeneities played a significant role in the eventual oxidant distribution and TCE/DNAPL removal.

- TCE/DNAPL removal efficiency was highest in the Upper Sand Unit, indicating that oxidant was effectively distributed in the looser, coarse-grained soil.
- TCE/DNAPL removal efficiency was lowest in the Middle Fine-Grained Unit, indicating that oxidant distribution was difficult in the tighter, fine-grained soil.
- Assessing the 15 ft of plot underneath the Engineering Service Building from oxidant injection points located outside the building proved difficult and resulted in low TCE/DNAPL removal efficiency under the building. This indicates that the radius of influence of the oxidant around the injection points was less than 15 ft.

### 5.2 Changes in Aquifer Characteristics

This section describes the short-term changes in aquifer characteristics created by the chemical oxidation application at Launch Complex 34, as measured by monitoring conducted before, during, and immediately after the demonstration. The affected aquifer characteristics are grouped into three subsections:

- Changes in CVOC levels (see Appendix C for detailed results)
- Changes in aquifer geochemistry (see Appendix D for detailed results)

- Changes in the hydraulic properties of the aquifer (see Appendix B for detailed results).

Table 5-4 lists the pre- and postdemonstration levels of various groundwater parameters that are indicative of

**Table 5-4.** Pre- and Postdemonstration Levels of Groundwater Parameters Indicative of Aquifer Quality

Groundwater Parameter (applicable groundwater standard, if any) (mg/L)	Aquifer Depth	Predemonstration (mg/L) <sup>(a)</sup>	Postdemonstration (mg/L) <sup>(a)</sup>
TCE (0.003)	Shallow	298 to 1,140	<0.005 to 630
	Intermediate	868 to 1,190	<0.005 to 360
	Deep	752 to 1,160	<0.005 to 220
DCE (0.070)	Shallow	3.9 to 12.5	<0.005 to 52.0
	Intermediate	4.1 to 21.3	<0.005 to 0.015
	Deep	9.18 to 44.5	<0.005 to <17.0
Vinyl chloride (0.001)	Shallow	<5.0	<0.010 to <33.0
	Intermediate	<5.0	<0.010 to <33.0
	Deep	<5.0	<0.010 to <20.0
pH	Shallow	7.0 to 7.4	7.2
	Intermediate	7.3 to 7.6	6.6 to 9.2
	Deep	7.4 to 7.5	6.4
ORP	Shallow	-149 to -25 mV	-2 mV
	Intermediate	-165 to -38 mV	-97 to 384 mV
	Deep	-150 to -22 mV	-84 mV
DO	Shallow	<0.5 to 2.7	<0.5
	Intermediate	0.50 to 0.9	<0.5 to 3.1
	Deep	<0.5 to 0.9	0.7
Calcium	Shallow	70	4 to 70
	Intermediate	41	4 to 49
	Deep	84 to 88	210 to 349
Magnesium	Shallow	53	2 to 111
	Intermediate	59	3 to 19
	Deep	82 to 84	53 to 203
Alkalinity	Shallow	269 to 316	1,060 to 1,500
	Intermediate	291 to 323	1,280
	Deep	204 to 208	1,300 to 2,140
Chloride (250)	Shallow	38 to 53	236 to 237
	Intermediate	57 to 181	238 to 582
	Deep	722 to 752	1,360 to 1,730
Manganese (0.050)	Shallow	0.016 to 1	2 to 235
	Intermediate	<0.015 to 0.018	98 to 516
	Deep	0.015 to 0.025	9 to 10
Iron (0.3)	Shallow	0.3 to 2.5	<0.05
	Intermediate	<0.05 to 0.5	<0.1
	Deep	0.1 to 0.3	<0.05 to 1.1
Sulfate	Shallow	29 to 46	483
	Intermediate	49 to 138	1,380
	Deep	67 to 103	379 to 535
TDS (500 )	Shallow	387 to 499	2,860 to 6,790
	Intermediate	503 to 760	5,280 to 13,000
	Deep	1,490 to 1,550	5,990 to 6,410
BOD	Shallow	<3	<3 to 112
	Intermediate	<3 to 16	<3
	Deep	13	16 to 108
TOC	Shallow	4 to 6	157 to 422
	Intermediate	6 to 16	86 to 2,110
	Deep	10 to 11	10 to 131

(a) All reported quantities are in mg/L, except for pH, which is in log units, and ORP, which is in mV.

aquifer quality and the impact of the oxidative treatment. Other important organic and inorganic aquifer parameters are discussed in the text. A separate microbiological evaluation of the aquifer is described in Appendix E.

### **5.2.1 Changes in CVOC Levels in Groundwater**

The considerable DNAPL mass removed was expected to reduce CVOC levels in groundwater, at least in the short term. Although influx from surrounding contamination is possible, it was not expected to contribute significantly to the postdemonstration sampling in the short term because through most of the demonstration, hydraulic gradients radiated outward from the plot due to the injection pressures inside the plot. Also, the natural gradient at the site is relatively flat, so any influx of contaminated groundwater into the plot between oxidant injection and sampling was expected to be minimal. Lastly, excess permanganate in many parts of the plot would help control CVOC influx. Therefore, CVOC levels were measured in the Oxidation Plot wells before, during, and after the demonstration to evaluate short-term changes in CVOC levels in the groundwater.

Appendix C tabulates the levels of TCE, *cis*-1,2 DCE and vinyl chloride in the groundwater in the Oxidation Plot wells. Figures 5-8 to 5-10 show dissolved TCE concentrations in the shallow, intermediate, and deep wells in the Oxidation Plot and perimeter. Before the demonstration, several of the shallow, intermediate, and deep wells in the plot had concentrations close to the solubility of TCE (1,100 mg/L). Immediately after the demonstration, TCE concentrations in several of these wells (e.g., BAT-1S, BAT-2S, BAT-2I, and BAT-6D) declined by 99% or more. The only anomalous well was the Upper Sand Unit Well BAT-5S. Both during and after the demonstration, BAT-5S showed increased TCE concentrations, at times approaching saturation levels. SB219, the soil core closest to BAT-5S (the only monitoring well that showed an increase in TCE concentrations throughout the demonstration) did not indicate any substantial amounts of DNAPL (see Figure 5-1). This indicates the following possibilities:

- Local heterogeneities near BAT-5S may have prevented sufficient oxidant from reaching this region, as well as perhaps other regions in the plot. In many wells inside the Oxidation Plot, the water turned purple during the demonstration, indicating excess permanganate and good oxidant distribution. However, in some wells in the plot, the water never turned purple, indicating that preferential pathways dominated flow and oxidant distribution on the scale of the plot. Local heterogeneities may limit the amount of oxidant encountered

through advective flow in certain regions of the plot; some of these regions may be relatively close to oxidant injection points. Over time, it is possible that permanganate may persist in the vicinity long enough to penetrate into such difficult spots by diffusion.

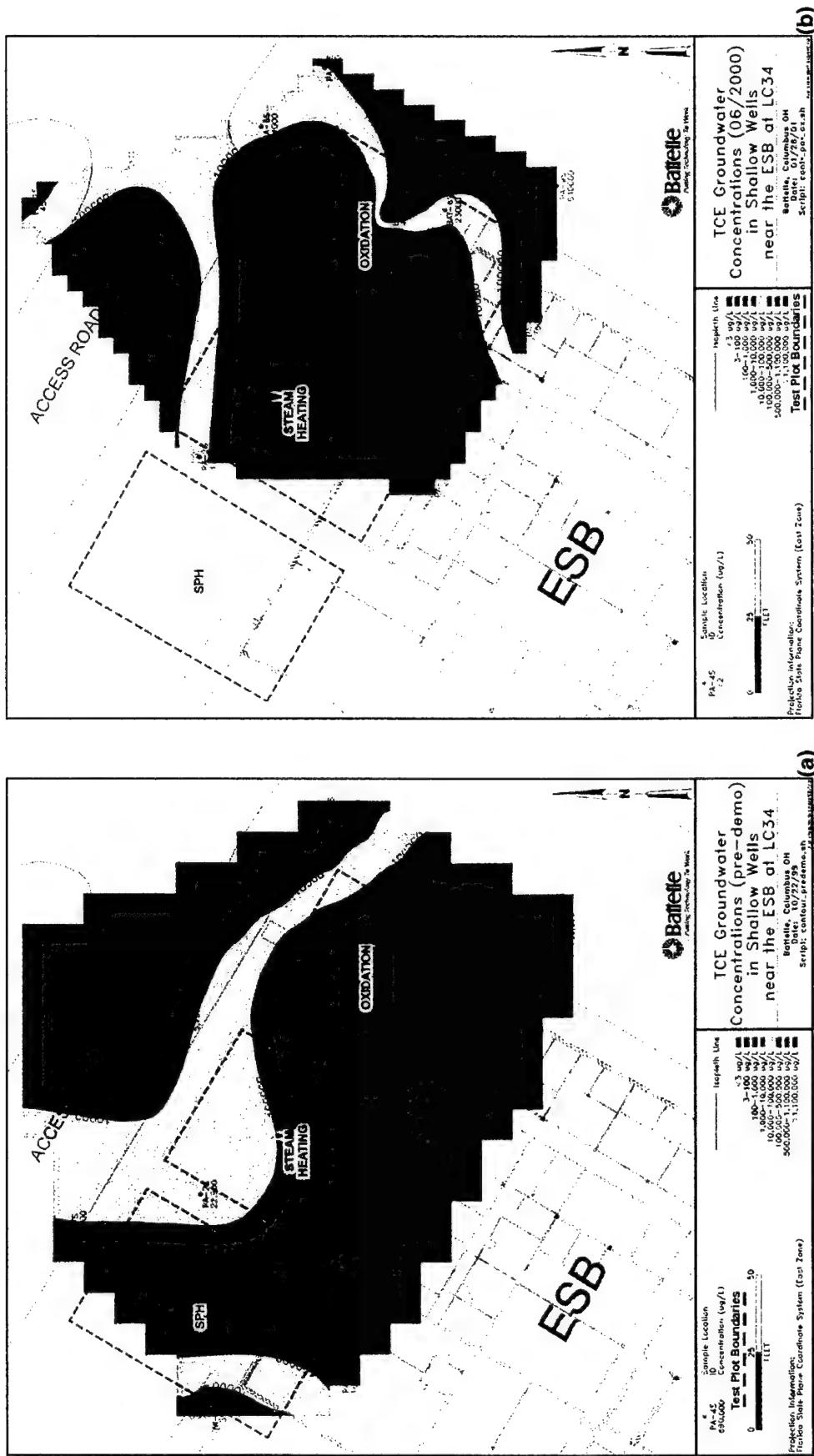
- Redistribution of residual DNAPL within the plot due to hydraulic gradients is unlikely; residual DNAPL does not move out of pores by hydraulic gradient alone. On the other hand, there may have been some mobile DNAPL in the plot that migrated into the BAT-5S well early during the injection and subsequently created elevated TCE levels in the well. This may indicate that, when such high DNAPL concentrations are present at a site, it may be desirable to pump some groundwater before oxidant injection to remove any mobile DNAPL that may migrate under injection gradients.
- Another possibility is that the sharp increase in TCE in BAT-5S and some perimeter wells (see Section 5.2.2) is due to the increased groundwater flow through previously less permeable regions of the DNAPL source zone. Partial removal of DNAPL by oxidation increases the permeability of the DNAPL source regions to groundwater flow (Pankow and Cherry, 1996). Therefore, DNAPL mass removal, if it is not 100%, can initially elevate dissolved TCE concentrations, although in subsequent years, reduced dissolved-TCE levels will result.

The concentration of *cis*-1,2 DCE declined considerably in several wells (e.g., BAT-1S, BAT-2S, BAT-3D, BAT-6D, PA-4S, and PA-4I) within the plot. However, some wells (e.g., BAT-3I) showed an increase in *cis*-1,2 DCE levels. It is unclear whether there was a net removal or redistribution of *cis*-1,2 DCE. Vinyl chloride was not detected in several wells both before and after the demonstration, primarily because of the analytical limitations associated with samples containing higher levels of TCE.

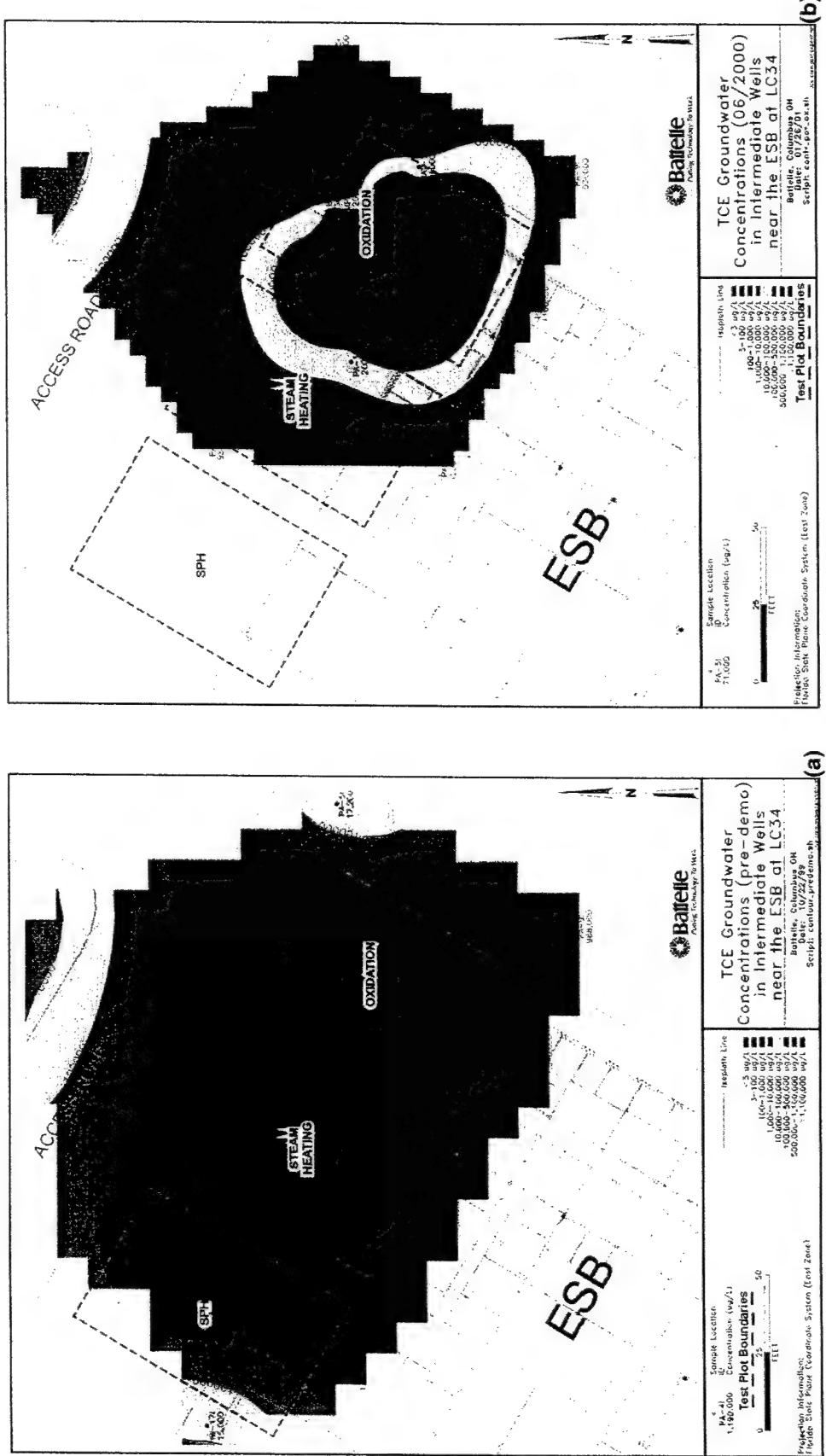
### **5.2.2 Changes in Aquifer Geochemistry**

Among the field parameter measurements (tabulated in Appendix D) conducted in the affected aquifer before, during, and after the demonstration, the following trends were observed:

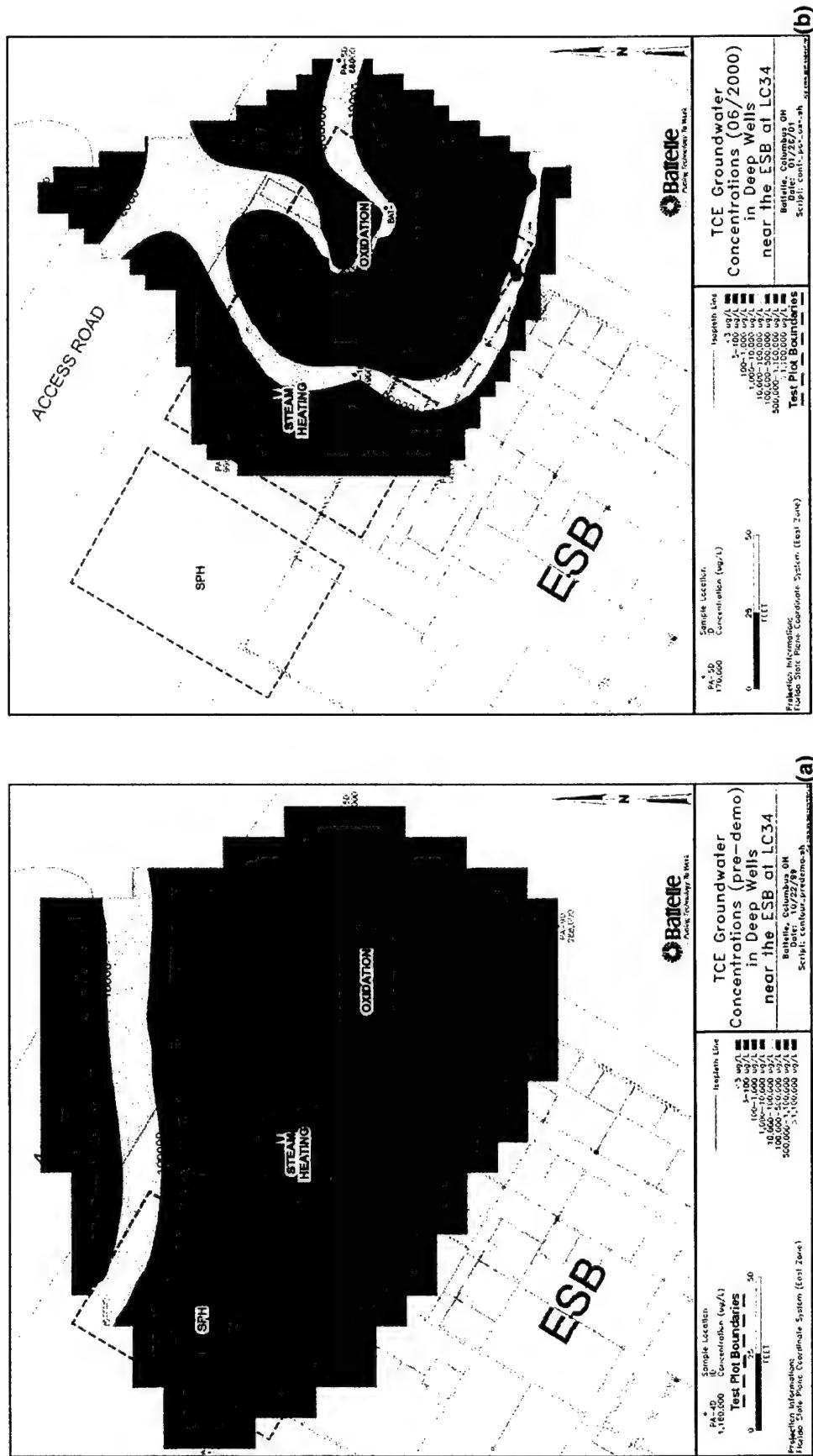
- Groundwater temperature ranged from 26 to 29°C before the demonstration to 27 to 29°C after the demonstration (relatively unchanged). This was expected as there is no exothermic reaction involved with permanganate, as with other oxidants.



**Figure 5-8.** Dissolved TCE Concentrations ( $\mu\text{g}/\text{L}$ ) during (a) Pre-demonstration and (b) Postdemonstration Sampling of Shallow Wells



**Figure 5-9.** Dissolved TCE Concentrations ( $\mu\text{g/L}$ ) during (a) Predemonstration and (b) Postdemonstration Sampling of Intermediate Wells



**Figure 5-10.** Dissolved TCE Concentrations ( $\mu\text{g/L}$ ) during (a) Predemonstration and (b) Postdemonstration Sampling of Deep Wells

- Groundwater *pH* ranged from 7.0 to 7.6 before the demonstration to 6.4 to 9.2 after the demonstration, with some fluctuation during the demonstration. A pH drop would be expected in an unbuffered system as the oxidation reaction produces hydrogen ions and CO<sub>2</sub>. However, as discussed in Section 5.3.1, the native groundwater alkalinity and carbonate shell materials provide a buffer, and limit any change in pH.
- *ORP* increased from -22 to -165 mV before the demonstration to -97 to 384 mV after the demonstration, with some fluctuation during the demonstration. The higher ORP is indicative of the oxidizing conditions created in the plot.
- *DO* ranged from 0.3 to 2.7 mg/L before the demonstration to 0.3 to 3.0 mg/L after the demonstration, with some fluctuation during the demonstration. Some DO may have been introduced into the aquifer through the hydrant water used to make up the permanganate solution. Due to the limitations of measuring DO with a flowthrough cell, groundwater with DO levels below 0.5 is considered anaerobic. Except for the shallower regions, the aquifer was mostly anaerobic through the demonstration.
- *Conductivity* increased from 0.5 to 2.7 mS/cm before the demonstration to 6.7 to 14.6 mS/cm after the demonstration. The increase is attributed to a buildup of dissolved ions formed from the mineralization of organic matter and CVOCs.

Other groundwater measurements indicative of aquifer quality included inorganic ions, BOD, and TOC. The results of these measurements are as follows:

- *Calcium* and *magnesium* levels remained relatively unchanged in the shallow and intermediate wells, but increased in the deep wells. In the deep wells, predemonstration levels of calcium (84 to 88 mg/L) and magnesium (82 to 84 mg/L) rose to postdemonstration levels of 210 to 349 mg/L (calcium) and 53 to 203 mg/L (magnesium). Groundwater *alkalinity* increased from 204 to 323 mg/L before the demonstration to 1,060 to 2,140 mg/L after the demonstration. The sharp changes in calcium, magnesium, and alkalinity can be attributed to the oxidation of organic matter and CVOCs that leads to CO<sub>2</sub> generation in the aquifer, and the interaction of this CO<sub>2</sub> with shell material and groundwater in open (shallow aquifer) and closed (deep aquifer) systems, as described in Section 5.3.1.
- *Chloride* levels were already relatively high in the aquifer due to saltwater intrusion, especially in the

deeper units. Despite relatively high native chloride levels in the aquifer and despite the dilution effect of hydrant water containing 94 mg/L that was used to make up the permanganate injection solution, chloride concentrations increased noticeably in the three stratigraphic units. In the shallow wells, chloride increased from 38 to 53 mg/L before the demonstration to 236 to 237 mg/L after the demonstration. In the intermediate wells, chloride increased from 57 to 181 mg/L before the demonstration to 238 to 582 mg/L after the demonstration. In the deep wells, chloride levels increased from 722 to 752 mg/L before the demonstration to 1,360 to 1,730 mg/L after the demonstration. These increased chloride levels are a primary indicator of CVOC destruction due to chemical oxidation. The secondary drinking water limit for chloride is 250 mg/L.

- *Manganese* levels in the plot rose from <0.015 to 1.1 mg/L before the demonstration to as high as 516 mg/L in BAT-5I after the demonstration; manganese has a secondary drinking water limit of 0.05 mg/L, which was exceeded during and after the demonstration. Perimeter wells also showed elevated levels of manganese. Dissolved manganese consists of the species Mn<sup>7+</sup> (from excess permanganate ion) and Mn<sup>2+</sup> (generated when MnO<sub>2</sub> is reduced by native organic matter). Manganese levels are expected to subside over time, as excess permanganate precipitates out as MnO<sub>2</sub> and normal groundwater flow reestablishes in the plot.
- *Iron* levels in the Oxidation Plot remained relatively unchanged at levels of <0.05 to 2.5 mg/L in the native groundwater and <0.05 to 1.1 mg/L in the postdemonstration water; the secondary drinking water limit for iron is 0.3 mg/L, which was exceeded during and after the demonstration. Precipitation of ferric iron on soil was visually noted (as orange color) and the expectation was that dissolved iron levels would decrease. Some dissolution of iron from underground materials could have occurred that replenished dissolved iron. The monitoring wells are made of stainless steel and are fairly resistant to the oxidant; however, chloride may corrode stainless steel and dissolve some iron and, perhaps, chromium.
- *Sulfate* levels increased sharply from 29 to 138 mg/L before the demonstration to 379 to 1,380 mg/L after the demonstration. This increase in sulfate may be due to oxidation of reduced sulfur species in the native soil.
- *TDS* levels increased considerably in all three units. In the shallow wells, TDS levels rose from

387 to 499 mg/L before the demonstration to 2,860 to 6,790 mg/L after the demonstration; in the intermediate wells, TDS rose from 517 to 760 mg/L before to 5,280 to 13,000 mg/L after the demonstration; in the deep wells, TDS rose from 1,490 to 1,550 mg/L before to 5,990 to 6,410 mg/L after the demonstration. The secondary drinking water limit for TDS is 500 mg/L, which was exceeded both before and after the demonstration.

- Table 5-5 shows the groundwater cleanup target levels issued by the State of Florida for 12 trace metals. Trace metals enter the aquifer through the industrial-grade potassium permanganate used to make up the injected oxidant solution. The primary drinking water limits for chromium, nickel, and thallium were exceeded in some of the Oxidation Plot wells during and after the demonstration. The secondary drinking water standard for aluminum was exceeded on one occasion during the demonstration, but subsided after the demonstration. The short-term buildup of trace metals in the treatment zone is interesting, given the fact that there generally was a strong hydraulic gradient dissipating dissolved species radially away from the plot (see Section 5.3.2). Chromium (PA-3S, PA-5S, and PA-12D) and nickel (PA-5S and PA-12 cluster) limits were also exceeded in some of the perimeter wells. In addition to the industrial-grade permanganate, another source of chromium may be the stainless steel monitoring wells, which, although resistant to the oxidant, may be corroding due to the high chloride levels in

the water. Elevated levels of trace metals in the treated aquifer are expected to eventually subside by advection and diffusion over time.

- TOC and BOD data were difficult to interpret. TOC in groundwater ranged from 4 to 16 mg/L before the demonstration and from 10 to 2,110 mg/L after the demonstration. BOD declined in some wells, increased in other wells, and remained unchanged in some wells, indicating the variations in the efficiency of oxidant distribution in different regions of the plot. BOD increased sharply in BAT-5S and BAT-5D, from <3 to 13 mg/L before the demonstration to 98 to 112 mg/L after the demonstration. The increase in groundwater TOC and BOD may indicate greater dissolution of native organic species in the groundwater due to oxidation. TOC levels measured in soil remained relatively unchanged, ranging from 0.9 to 1.8% before the demonstration and from 0.8 to 1.8% after the demonstration.

In addition to measuring inorganic parameters in the Oxidation Plot wells, they also were measured in the perimeter wells surrounding the plot and selected distant wells to see how far the influence of the chemical oxidation would progress. In addition to the geochemistry, the effect of the chemical oxidation treatment on the aquifer microbiology was evaluated in a separate study as described in Appendix E.

### **5.2.3 Changes in the Hydraulic Properties of the Aquifer**

Table 5-6 summarizes the results (see Appendix B) of slug tests conducted in the Oxidation Plot before and after the demonstration. Hydraulic conductivity of the aquifer ranged from 1.3 to 6.4 ft/day before the demonstration to 1.4 to 5.0 ft/day after the demonstration. There was no noticeable difference in the hydraulic conductivity due to the chemical oxidation treatment. Any buildup of MnO<sub>2</sub> or other solids due to the chemical

**Table 5-5.** Postdemonstration Concentrations of Trace Metals in Groundwater at Launch Complex 34 versus the State of Florida Limits (issued May 26, 1999)

Trace Metal	Maximum Concentration Measured in Treated Aquifer ( $\mu\text{g/L}$ )	State of Florida Drinking Water Limit ( $\mu\text{g/L}$ )	Standard
Aluminum	<200	200	Secondary
Antimony	<6	6	Primary
Arsenic	21	50	Primary
Barium	<200	2,000	Primary
Beryllium	<10	4	Primary
Chromium	193,000	100	Primary
Copper	<25	1,000	Secondary
Lead	12	15	Primary
Nickel	10,600	100	Primary
Silver	38	100	Secondary
Thallium	20	2	Primary
Zinc	56	5,000	Secondary

**Table 5-6.** Pre- and Postdemonstration Hydraulic Conductivity in the Oxidation Plot Aquifer

Well	Hydraulic Conductivity (ft/day)	
	Predemonstration	Postdemonstration
BAT-5S	4.0	5.0
BAT-6S	5.1	Poor response
BAT-3I	1.6	2.4
BAT-5I	6.4	1.5
BAT-6I	1.4	3.7
BAT-3D	1.3	Poor response
BAT-6D	2.3	1.4

oxidation process does not seem to have affected the hydraulic properties of the aquifer.

#### **5.2.4 Summary of Changes in Aquifer Quality**

In summary, application of the chemical oxidation technology created the following short-term changes in the aquifer:

- Dissolved TCE levels declined sharply in most parts of the treated aquifer. In monitoring well BAT-5S, TCE levels increased, possibly due to a redistribution of DNAPL and/or redistribution of groundwater flow in the source zone.
- Temperature, pH, and DO remained relatively stable through the demonstration. ORP and conductivity of the groundwater increased, indicating oxidizing conditions and accumulation of dissolved ions.
- Calcium and magnesium levels rose in the deeper groundwater, indicating interactions with the shell material in the semiconfined lower stratigraphic units (see Section 5.3.1).
- Alkalinity, chloride, and total dissolved solids levels rose sharply, indicating oxidation of TCE and native organic matter with carbon dioxide generation (see Section 5.3.1). High chloride and TDS levels both before and after the demonstration cause the groundwater to be classified as brackish.
- Dissolved manganese levels in the plot rose above secondary drinking water limits following the demonstration.
- Dissolved sulfate levels rose, indicating interactions between the oxidant and soil matter.
- Some trace metals, namely chromium, nickel, and thallium, which were introduced into the aquifer through the industrial-grade potassium permanganate exceeded State of Florida drinking water limits following the demonstration. These elevated levels are expected to subside over time as normal groundwater flow is restored.
- The geochemical interactions between the oxidant and the aquifer are relatively complex, and not all of the aquifer changes were easy to explain. The persistence of dissolved iron, the variability of BOD, the increase in sulfate, and the persistence of TOC in the postdemonstration aquifer are difficult to explain without geochemical modeling.

#### **5.3 Fate of the TCE/DNAPL Mass Removed**

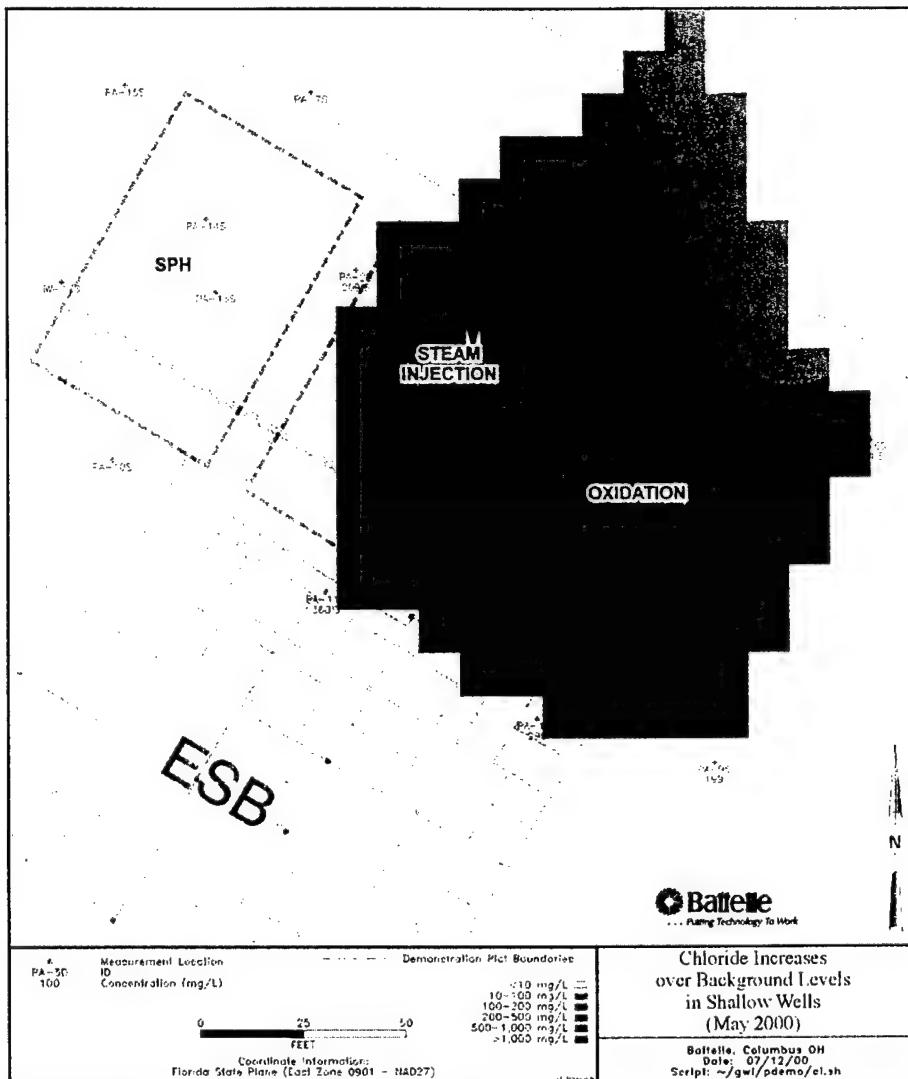
This part of the assessment was the most difficult because there are several pathways that the DNAPL could take when subjected to the chemical oxidation treatment. These pathways were evaluated as follows:

##### **5.3.1 DNAPL Destruction through Oxidation of TCE**

As described in Equations 5-1 and 5-2, oxidation of TCE and other CVOCs by permanganate leads to the formation of chloride, carbon dioxide, hydrogen ion, and manganese dioxide. Any manganese dioxide generated is insoluble in water and is expected to deposit on the soil surfaces — the brown discoloration of soil observed in some soil samples is indicative of manganese dioxide formation. The soluble or partially soluble species — chloride, carbon dioxide, carbonate (alkalinity), and hydrogen ion (pH) — are more amenable to more direct measurement.

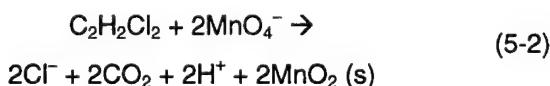
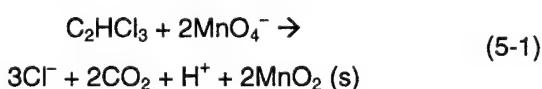
Chloride is the strongest indicator of TCE oxidation, because it is directly traceable to TCE; because of the high injection pressures (and high water levels) in the Oxidation Plot during chemical oxidation treatment, not much chloride intrusion is expected from tidal influence over the time period of the demonstration. Chloride generation due to oxidation would be expected to cause chloride levels to rise in the aquifer. Appendix D shows the pre- and postdemonstration chloride levels in the Oxidation Plot and surrounding aquifer. The increased chloride concentrations are noticeable in all three units — Upper Sand Unit, Middle Fine-Grained Unit, and Lower Sand Unit — even though predemonstration chloride levels were high to begin with. Chloride levels in the aquifer increased to levels that were above any contribution from the hydrant water (94 mg/L chloride content) used to make up the oxidant solution.

Figures 5-11 to 5-13 show the distribution of excess chloride in the shallow, intermediate, and deep wells, as measured in April 2000, towards the end of the chemical oxidation treatment. The chloride concentrations in this figure are the differences in chloride levels between the treated (postdemonstration) and native (predemonstration) levels of chloride. The strongest increase in chloride was observed in the deep wells (Lower Sand Unit), where the predemonstration DNAPL mass was highest. Because oxidation of TCE occurs in the aqueous phase, the treatment kinetics may be driven by the rate of dissolution of DNAPL, rather than the oxidation of dissolved TCE, which is a relatively fast process. The chloride



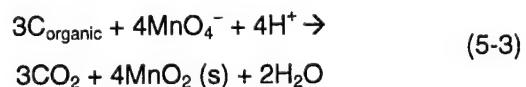
**Figure 5-11.** Distribution of Chloride Produced by Oxidation Technology in Shallow Wells near the Engineering Service Building at Launch Complex 34 (May 2000)

formed migrates radially out from the plot under the strong hydraulic gradients created by the oxidant injection.

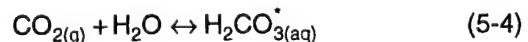


*Carbon dioxide* is an indicator of oxidation, although not of TCE alone. Native organic matter that is oxidized also releases carbon dioxide (see Equation 5-3). However, TOC levels in the predemonstration groundwater and soil were relatively unchanged, or increased slightly (see Section 5.2.2), possibly due to the formation of new organic species from the complex native humic matter in

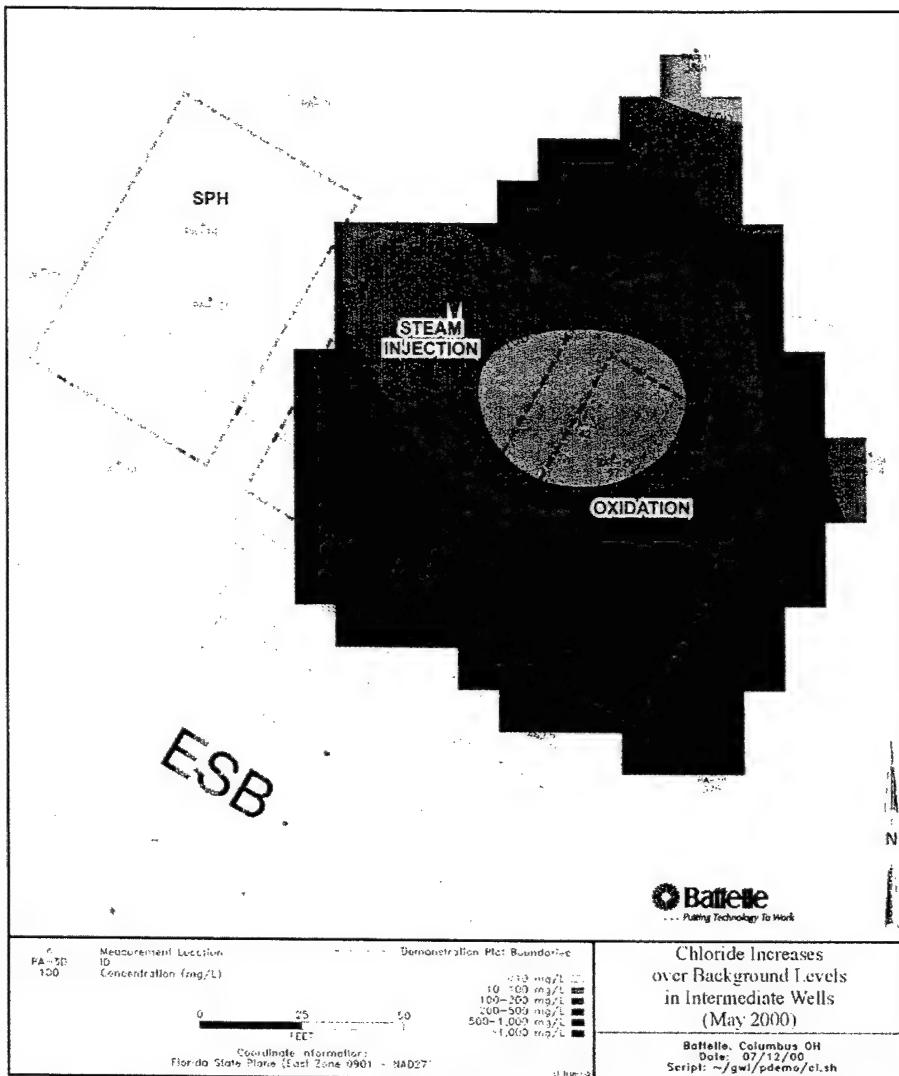
the soil. Formation of carbon dioxide is an encouraging sign that TCE and native organic matter are being oxidized.



In an unbuffered system, the CO<sub>2</sub> generated may be expected to lower the *pH* of the aquifer. Dissolution of gaseous CO<sub>2</sub> in water can be expressed according to the following mass action equation:



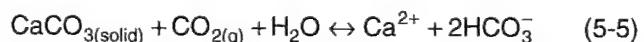
where H<sub>2</sub>CO<sub>3</sub><sup>\*</sup> represents both dissolved CO<sub>2</sub> (CO<sub>2(aq)</sub>) and carbonic acid (H<sub>2</sub>CO<sub>3</sub>). The predominant carbon



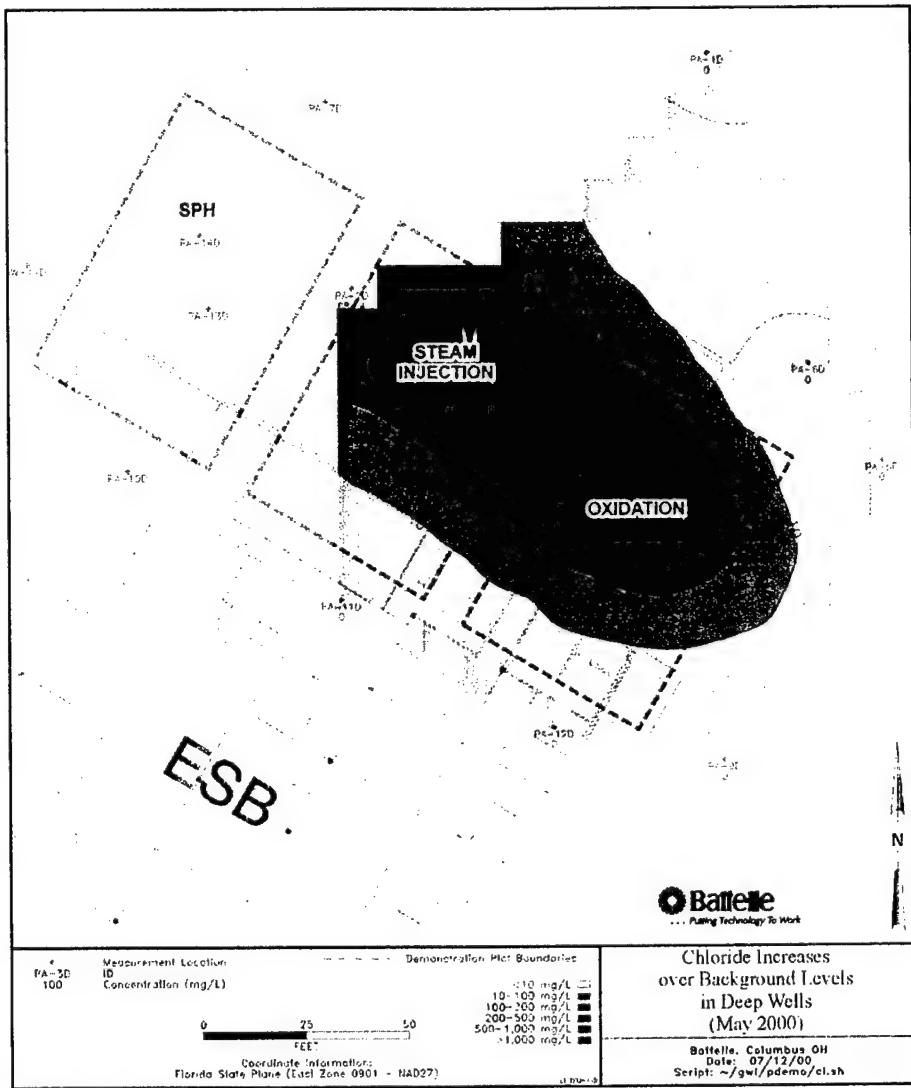
**Figure 5-12.** Distribution of Chloride Produced by Oxidation Technology in Intermediate Wells near the Engineering Service Building at Launch Complex 34 (May 2000)

species are  $\text{H}_2\text{CO}_3$  below pH 6.3;  $\text{HCO}_3^-$  between pH 6.3 and 10.3, and  $\text{CO}_3^{2-}$  above pH 10.3. The presence of carbonate species in the Launch Complex 34 groundwater provides buffering capacity, which attenuates the effects of the accumulating acidic species ( $\text{CO}_2$ ) in the water due to the oxidation treatment.

The other major factor in the geochemical scenario at Launch Complex 34 is the abundance of shell material in the aquifer soil. Carbonate rocks and biological shell material are composed primarily of calcium carbonate, and minor amounts of other metals, such as magnesium, iron, and manganese. Equilibrium between calcium carbonate (typically calcite or aragonite mineral forms) and water in the presence of  $\text{CO}_2$  can be expressed as Equation 7-5 (Appelo and Postma, 1994).



If a source of  $\text{CO}_2$  is available, calcite will dissolve. Oxidation of organic matter by permanganate causes generation of  $\text{CO}_2$ . While oxidation is occurring, the partial pressure of  $\text{CO}_2$  is probably high enough to cause a release of substantial amounts of calcium and bicarbonate ions into solution from the shell material. This could explain the sharp increase in alkalinity in all the Oxidation Plot wells, as well as the increase in dissolved calcium in some wells. Note that if calcite (shell material) were not available in the soil, the reaction in Equation 5-4 would apply, and the groundwater pH would have decreased accordingly. Therefore, despite the persistence of neutral pH and relatively low ORP in the posttreatment groundwater, the geochemistry indicates that a



**Figure 5-13.** Distribution of Chloride Produced by Oxidation Technology in Deep Wells near the Engineering Service Building at Launch Complex 34 (May 2000)

large amount of carbon dioxide was produced and a large portion of the organic matter (probably including the organic contaminants) was oxidized. The sharp increase in alkalinity and the substantial increase in inorganic chloride are encouraging signs that a significant proportion of the DNAPL removal was due to oxidation.

From a long-term perspective, it is important to note that after the CO<sub>2</sub> is exhausted, the system may not return to its original state, even though equilibrium is regained. In general, the aquifer environment is an open system, so the partial pressure of CO<sub>2</sub> does return to its normal level after oxidation subsides. However, during the period when CO<sub>2</sub> is being produced, the HCO<sub>3</sub><sup>-</sup> content increases logarithmically with pH, so that the final bicarbonate concentration at equilibrium is completely controlled by the initial partial pressure of CO<sub>2</sub> and the solubility of the

calcite in the shell material. Therefore, the only way for the alkalinity and calcium levels in the groundwater to return to pretreatment levels is through dilution with the groundwater from the surrounding aquifer. In the relatively stagnant aquifer at Launch Complex 34, this could take a long time. Rainfall and recharge from the ground surface also could play a role in the rebound.

In summary, all the geochemical indicators examined point to oxidation as a pathway that contributed substantially to the removal of TCE/DNAPL from the Oxidation Plot. These geochemical indicators include:

- Considerable rise in chloride levels in the treated aquifer
- Considerable increase in groundwater alkalinity (as indicative of carbon dioxide generation)

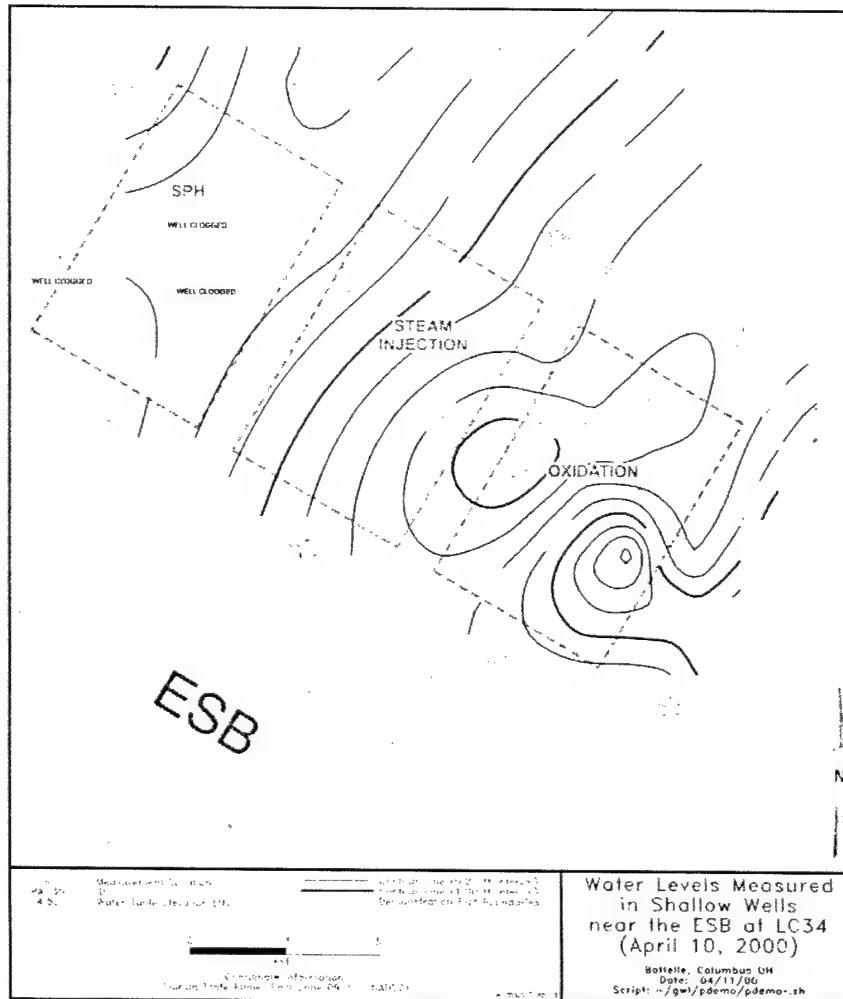
- Rise in calcium levels in the deeper, semiconfined portions of the aquifer.
- TCE concentrations in surface emissions to the atmosphere.

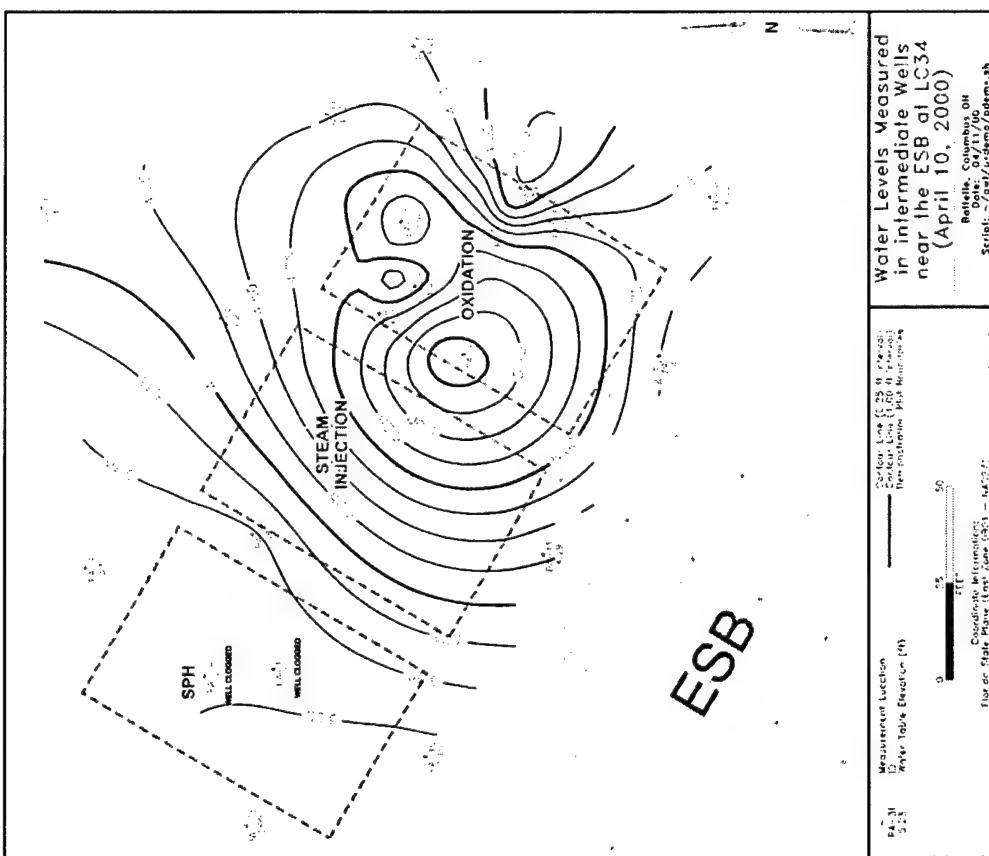
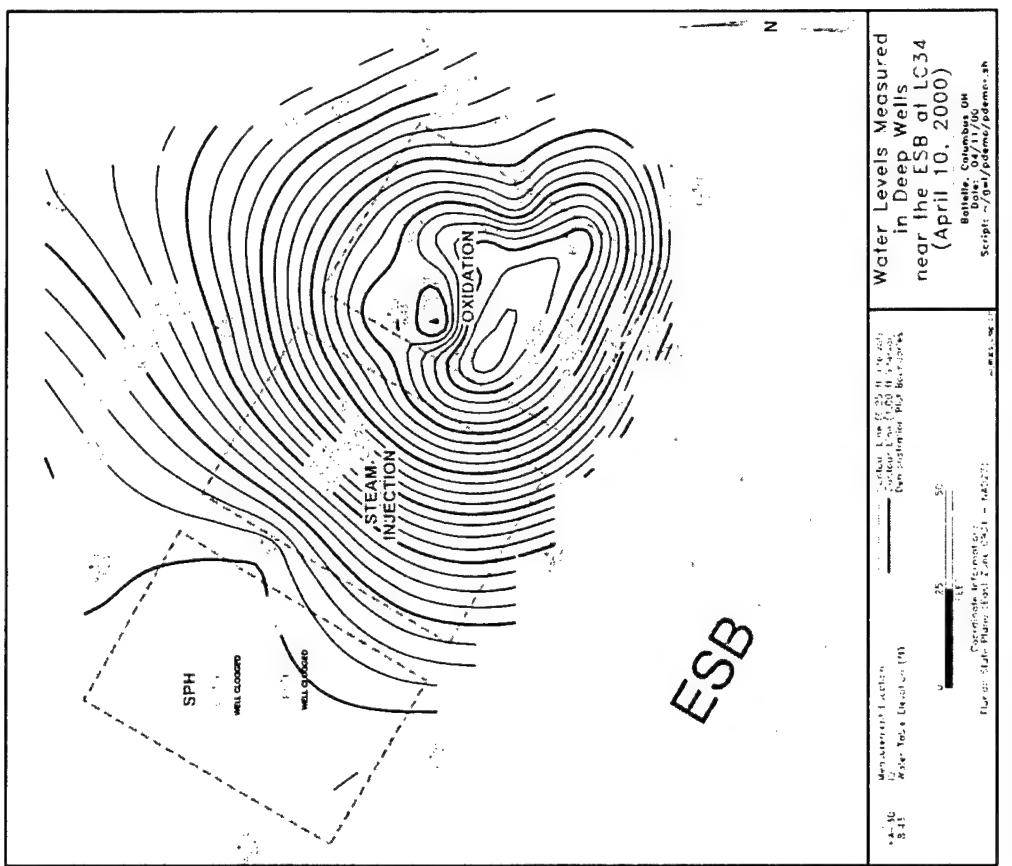
### 5.3.2 Potential for DNAPL Migration from the Oxidation Plot

The six measurements conducted to evaluate the potential for DNAPL migration to the surrounding aquifer include:

- Hydraulic gradient in the aquifer
- Distribution of dissolved potassium in the aquifer
- TCE measurements in perimeter wells
- TCE concentrations in the surrounding aquifer soil cores
- TCE concentrations in the vadose zone soil cores

As mentioned in Section 5.2, predemonstration *hydraulic gradients* in the Launch Complex 34 aquifer are relatively flat in all three stratigraphic units. During the demonstration, hydraulic gradients (see Figures 5-14 to 5-16) were measured in April 2000, while the third and final oxidant injection was under way in the Lower Sand Unit. Water level measurements in the deep wells showed a sharp hydraulic gradient emanating radially from the Oxidation Plot because of the injection pressures. Interestingly, the gradient was not as strong in the shallow and intermediate wells, indicating that the Middle Fine-Grained Unit acts as a conspicuous hydraulic barrier. Residual DNAPL cannot migrate due to hydraulic gradient alone, no matter how strong. However, if there was mobile DNAPL present in the aquifer, strong injection pressures could have caused DNAPL movement from the plot.



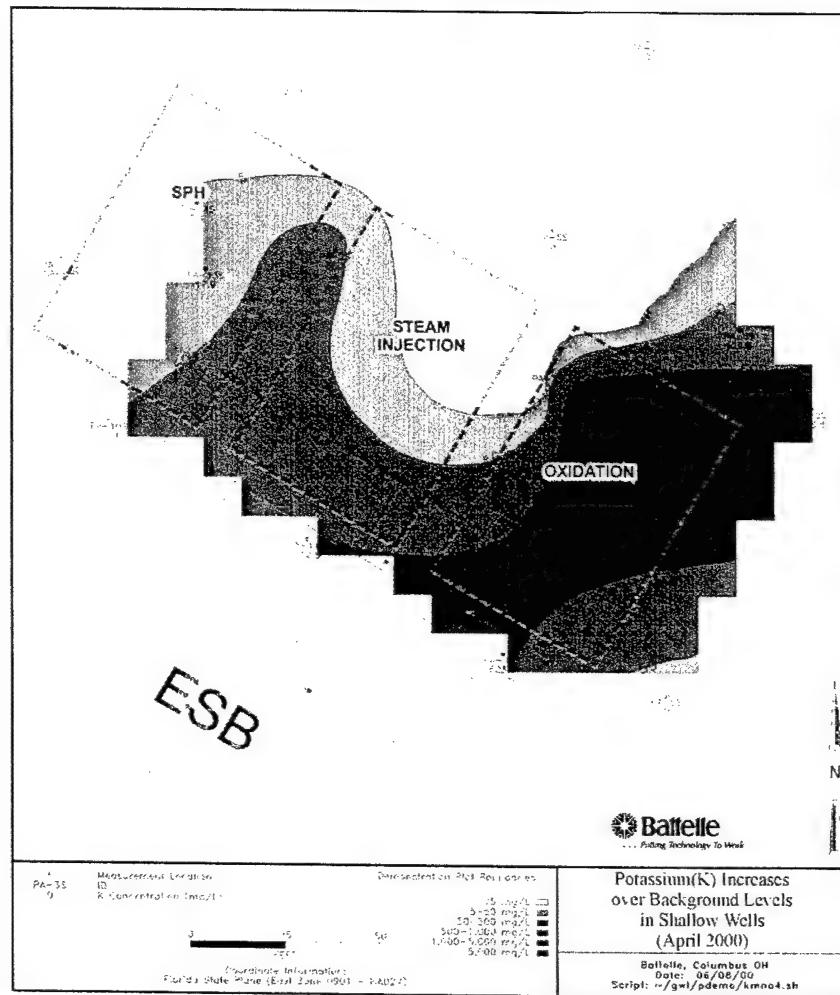


**Figure 5-16. Water Levels Measured in Deep Wells near the Engineering Service Building at Launch Complex 34 (April 2000)**

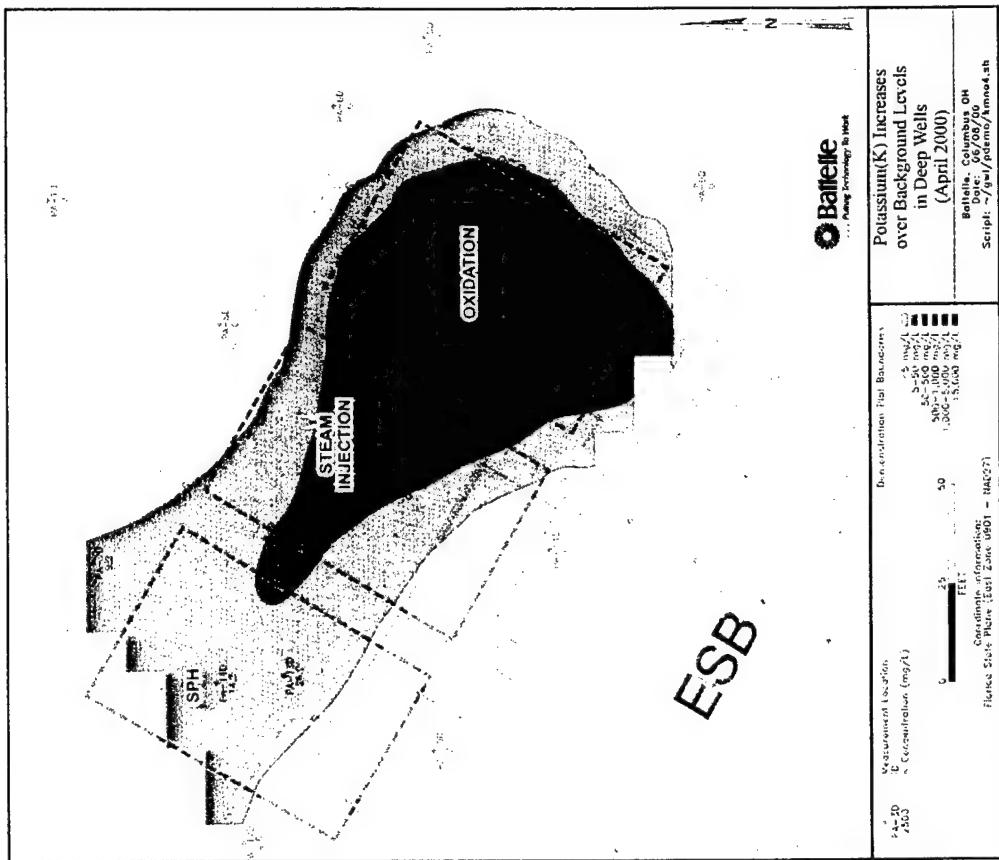
Migration of groundwater and dissolved groundwater constituents from the Oxidation Plot are exemplified by the movement of *potassium ion* in the aquifer, as shown in Figures 5-17 to 5-19. Potassium, originating from the injected oxidant, acts as a conservative tracer for tracking groundwater movement. Figures 5-17 to 5-19 show the excess potassium (above predemonstration levels) in the groundwater at Launch Complex 34. Because more monitoring wells are present on the western side of the Oxidation Plot, movement seems to be occurring to the west; however, similar groundwater transport probably occurred in all directions from the plot. This migration of groundwater and dissolved species from the Oxidation Plot is an important aspect of injecting oxidant without concomitant extraction or hydraulic control, and may need to be reviewed on a site-specific basis.

TCE and other CVOCs are among the dissolved species that migrated from the Oxidation Plot as indicated by the TCE measurements in perimeter and distant wells (see

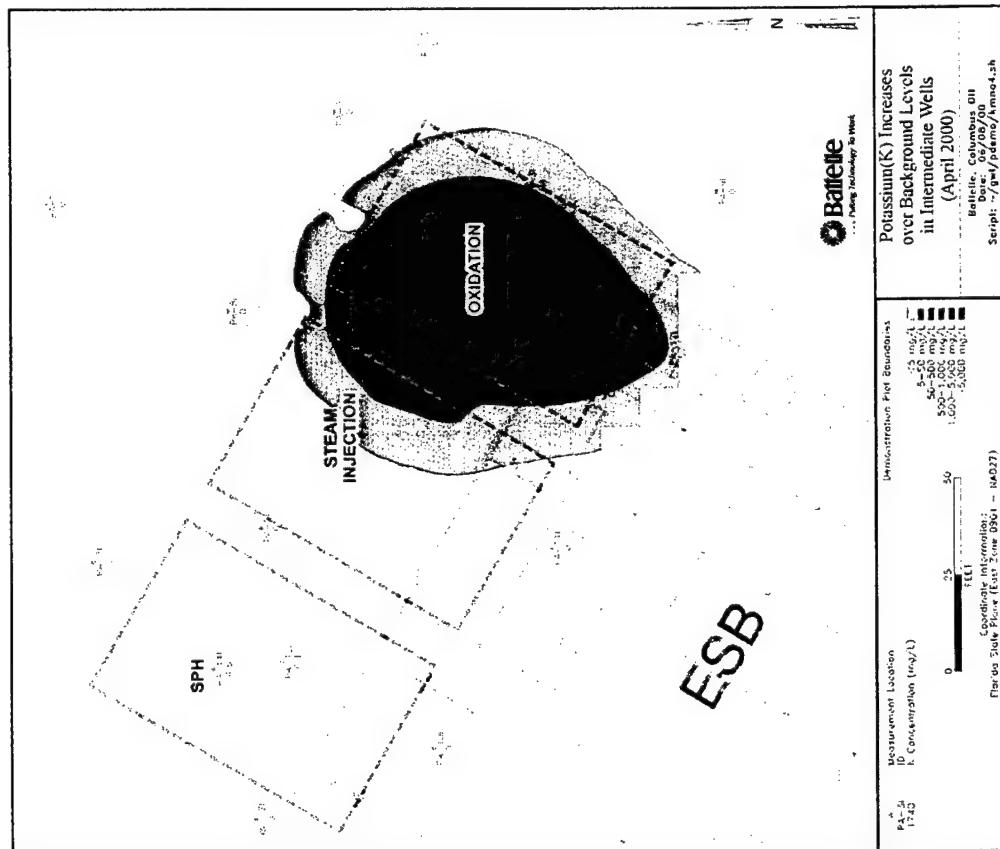
Appendix C). Figures 5-20 to 5-22 show the TCE trends observed in the *perimeter wells*. TCE levels in perimeter wells PA-5S, PA-5I, and PA-6S (on the northeast side of the Oxidation Plot) and in a somewhat distant well PA-8S (on the northwest side of the Oxidation Plot) rose sharply when the oxidation treatment started and an increase of over an order of magnitude was sustained through the end of the demonstration. In other perimeter wells, TCE levels either declined sharply or showed a mild increase. A sharp temporary increase in TCE concentrations in the monitoring wells would signify that dissolved-phase TCE has migrated. A sharp sustained increase may signify that DNAPL has redistributed within the plot or outside it. Another possibility, as mentioned in Section 5.2, is that the sharp increase in TCE in some Oxidation Plot and perimeter wells is due to the increased groundwater flow through previously less permeable regions of the DNAPL source zone; an increase in permeability can result in regions of the aquifer experiencing partial removal of DNAPL.



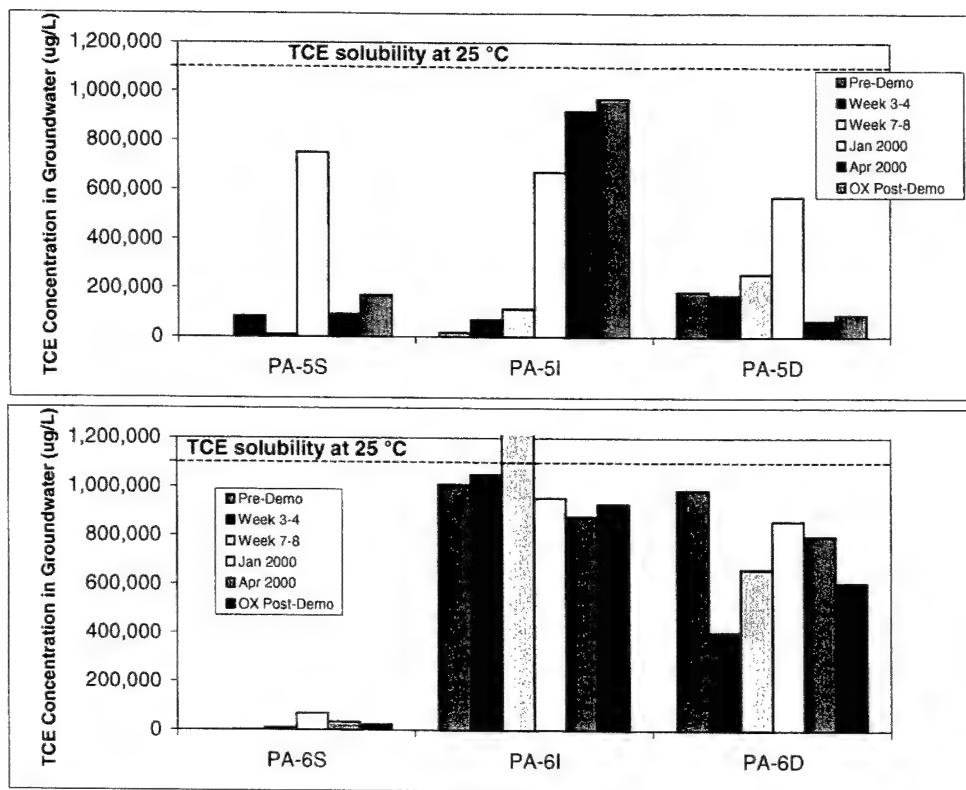
**Figure 5-17.** Distribution of Potassium (K) Produced by Oxidation Technology in Shallow Wells near the Engineering Service Building at Launch Complex 34 (April 2000)



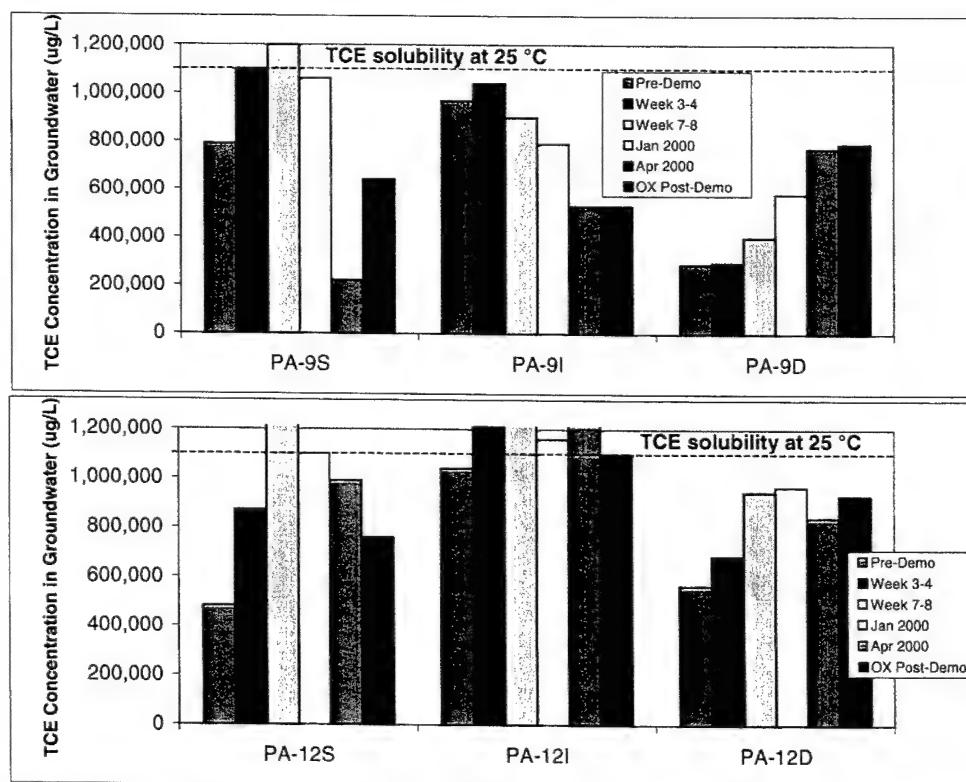
**Figure 5-19.** Distribution of Potassium (K) Produced by Oxidation Technology in Deep Wells near the Engineering Service Building at Launch Complex 34 (April 2000)



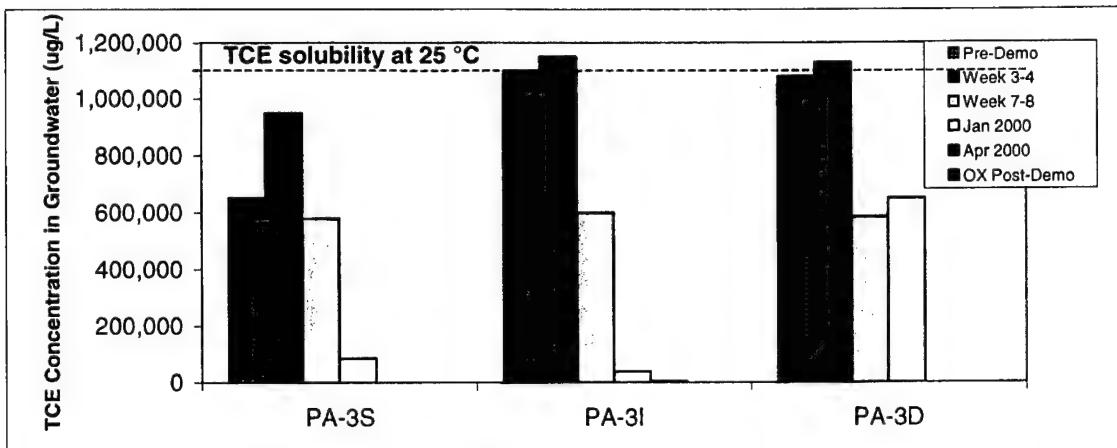
**Figure 5-18.** Distribution of Potassium (K) Produced by Oxidation Technology in Intermediate Wells near the Engineering Service Building at Launch Complex 34 (April 2000)



**Figure 5-20.** Dissolved TCE Levels ( $\mu\text{g}/\text{L}$ ) in Perimeter Wells on the Northeastern Side of the Oxidation Plot



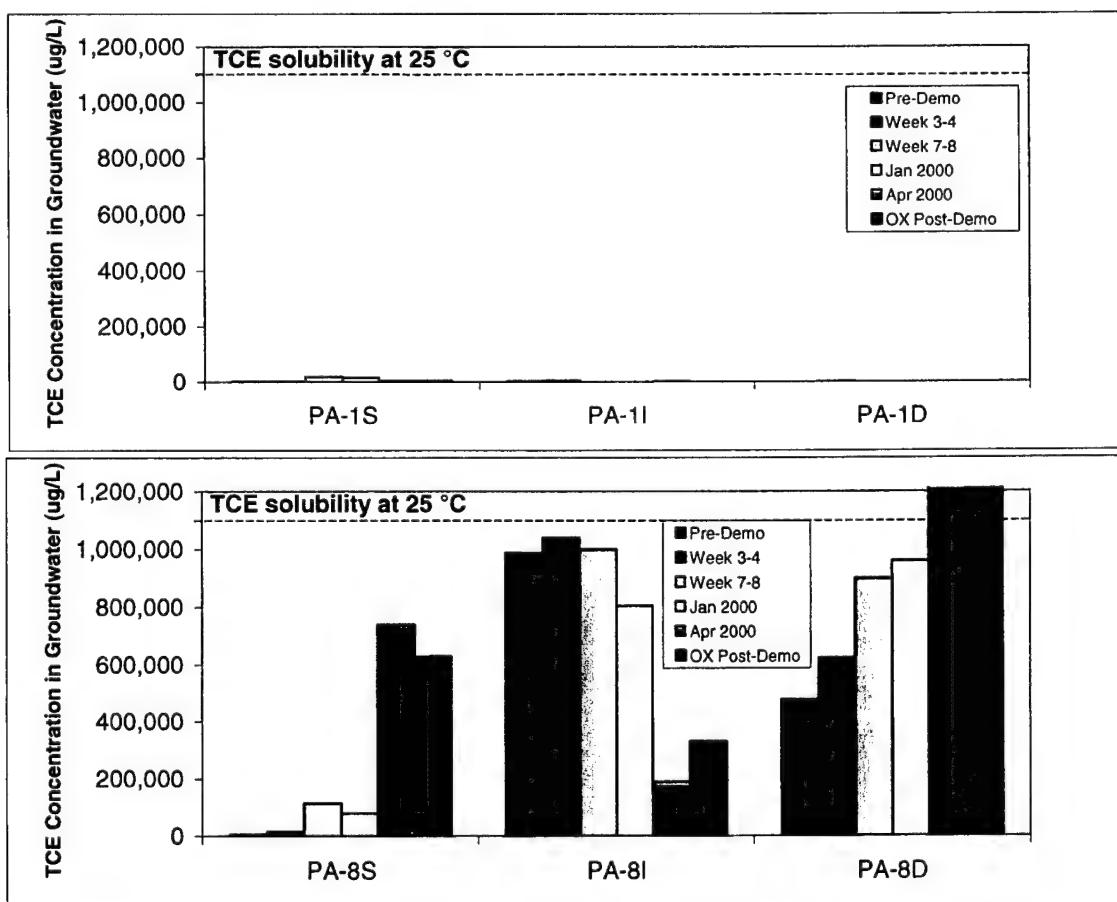
**Figure 5-21.** Dissolved TCE Levels ( $\mu\text{g}/\text{L}$ ) in Perimeter Wells on the Southern Side of the Oxidation Plot



**Figure 5-22.** Dissolved TCE Levels ( $\mu\text{g}/\text{L}$ ) in Perimeter Wells on the Western Side of the Oxidation Plot

Figure 5-23 shows the TCE trends observed in *distant well* clusters PA-8 and PA-1. PA-8 is closer to the Oxidation Plot on the northwest side. PA-1 is further away towards the north-northwest side. The PA-8 cluster showed a significant increase in TCE concentrations in the shallow and deep wells. After the oxidation and

SPH™ demonstrations started, DNAPL was observed for the first time in distant wells PA-11D, PA-2I, and PA-2D, all of which are on the west side of the Oxidation Plot. DNAPL had not been previously found in any of the monitoring wells before the demonstration. This indicates that some free-phase TCE movement occurred in



**Figure 5-23.** Dissolved TCE Levels ( $\mu\text{g}/\text{L}$ ) in Distant Wells on the Northwestern Side of the Oxidation Plot

the aquifer due to the application of the two technologies. It is unclear which of the two technologies contributed to the DNAPL movement and whether or not this DNAPL was initially in mobile or residual form. Mobile DNAPL could have moved under the influence of the sharp hydraulic gradient induced by the oxidant injection pressures alone. Residual DNAPL, by nature, would not be expected to move.

When the groundwater data indicated that DNAPL movement had occurred, additional postdemonstration soil cores were collected from areas surrounding the Oxidation Plot — at locations PA-206, PA-205, PA-209, PA-212, PA-211 and PA-208 (see Figure 4-3). These locations were selected because these were the only locations in the immediate vicinity of the Oxidation Plot where predemonstration soil core data were available for comparison. In none of these perimeter soil samples was there a noticeable increase in TCE or DNAPL concentration following the demonstration. The sampling density of the soil cores surrounding the plot is not as high as the sampling density outside the plot; therefore, the effort was more exploratory than definitive.

To evaluate the possibility of TCE/DNAPL migration to the vadose zone, all pre- and postdemonstration soil cores in the Oxidation Plot included soil samples collected at 2-ft intervals in the vadose zone. As seen in Figure 5-1, there was no noticeable deposition of TCE in the vadose zone soil due to the chemical oxidation treatment. Surface emission tests were conducted as described in Appendix F to evaluate the possibility of solvent losses to the atmosphere. As seen in Table 5-5, there was no noticeable difference in TCE concentrations between surface emission samples collected in the Oxidation Plot and at background locations at various times during and after the demonstration. Unlike some technologies that involve exothermic reactions or applied heating, permanganate oxidation does not cause volatilization of the targeted solvents and therefore there is very little probability of TCE losses to the vadose zone or atmosphere.

Because of NASA's concerns about breaching the relatively thin aquitard, no monitoring wells were installed during the demonstration into the Lower Clay Unit or in the aquifer below. Therefore, the potential for any downward migration of TCE cannot be evaluated.

### **5.3.3 Summary Evaluation of the Fate of TCE/DNAPL**

In summary, the field measurements indicate that DNAPL movement has occurred in the Launch Complex

34 aquifer due to the two technology demonstrations. It is unclear as to which of these two technologies caused this movement. It is also unclear as to whether the migrating DNAPL was initially present as mobile or residual form. If all the DNAPL was initially present in residual form, the strong hydraulic gradient created by the oxidant injection alone would not be sufficient to cause DNAPL to migrate. If some DNAPL was present in mobile form, the hydraulic gradient created by the injection pressures would cause it to migrate. In general, for future applications, the strong hydraulic gradients generated by the oxidant injection would necessitate that one or both of the following two measures be implemented:

- The DNAPL source zone boundary should be delineated as accurately as possible so that oxidant injection can be applied without extraction or other hydraulic control. In this scenario, either the oxidant injection pressures could be reduced in favor of longer injection times and/or the oxidant could be injected from the outside in (injection in the perimeter of the DNAPL source zone, followed by injection in the interior of the source zone).
- Oxidant injection could be accompanied by extraction or other hydraulic control so that the migration of any mobile DNAPL is contained.
- Pumping of the aquifer should be considered before oxidant injection to evacuate any mobile DNAPL that may be present in the source zone.

All of these alternatives pose their own challenges. In the first option, a definitive identification of the DNAPL source boundary may be difficult to achieve. In the second option, extraction of injected fluids may make the application more expensive due to the increased cost of extracting and extracting, treating, and disposing/reinjecting the recovered fluids. In the third option, considerable fluid could be generated above ground and require treatment before reinjection/disposal. At Launch Complex 34, the vendor was constrained to some extent by the conditions of the demonstration, in which only a portion of the DNAPL source was targeted for treatment, as well as by regulatory/economic restraints against extraction/reinjection.

## **5.4 Operating Requirements and Cost**

Section 3 contains a description of the chemical oxidation field operations at Launch Complex 34. Section 7 contains the costs and economic analysis of the technology.

## 6. Quality Assurance

A QAPP (Battelle, 1999d) prepared before the demonstration outlined the performance assessment methodology and the QA measures to be taken during the demonstration. The results of the field and laboratory QA for the critical soil and groundwater CVOC (primary) measurements and groundwater field parameter (secondary) measurements are described in this section. The results of the QA associated with other groundwater quality (secondary) measurements are described in Appendix G. The focus of the QA is on the critical TCE measurement in soil and groundwater, for which, in some cases, special sampling and analytical methods were used. For other measurements (chloride, calcium, etc.), standard sampling and analytical methods were used to ensure data quality.

### 6.1 QA Measures

This section describes the data quality in terms of representativeness and completeness of the sampling and analysis conducted for technology performance assessment. Chain-of-custody procedures are also described.

#### 6.1.1 Representativeness

Representativeness is a measure that evaluates how closely the sampling and analysis represents the true value of the measured parameters in the target matrices. The critical parameter in this demonstration is TCE concentration in soil. The following steps were taken to achieve representativeness of the soil samples:

- Statistical design for determining the number and distribution of soil samples in the 75-ft × 50-ft Oxidation Plot, based on the horizontal and vertical variability observed during a preliminary characterization event (see Section 4.1). Twelve locations (one in each cell of a 4 × 3 grid in the plot) were cored before and after the demonstration and a continuous core was collected and sampled in 2-ft sections from ground surface to aquitard at each coring location. At the 80% confidence level,

the pre- and postdemonstration TCE mass estimates in the plot (see section 5.1) were within relatively narrow intervals that enabled a good judgment of the mass removal achieved by the chemical oxidation technology.

- Sampling and analysis of duplicate postdemonstration soil cores to determine TCE concentration variability within each grid cell. Two complete cores (SB-217 and SB-317) were collected within about 2 ft of each other in the postdemonstration Oxidation Plot, with soil sampling at every 2-ft interval (see Figure 5-1 for the TCE analysis of these cores). The resulting TCE concentrations showed a relatively good match between the duplicate cores. This indicated that dividing the Oxidation Plot into 12 grid cells enabled a sampling design that was able to address the horizontal variability in TCE distribution.
- Continuous sampling of the soil column at each coring location enabled the sampling design to address the vertical variability in the TCE distribution. By extracting and analyzing the complete 2-ft depth in each sampled interval, essentially every vertical depth was sampled.
- Use of appropriate modifications to the standard methods for sampling and analysis of soil. To increase the representativeness of the soil sampling, the sampling and extraction procedures in EPA Method 5035 were modified so that an entire vertical section of each 2-ft core could be sampled and extracted, instead of the 5-g aliquots specified in the standard method (see Section 4.1). This was done to maximize the capture of TCE/ DNAPL in the entire soil column at each coring location.

Steps taken to achieve representativeness of the groundwater samples included:

- Installation and sampling of six well clusters in the 75-ft × 50-ft Oxidation Plot. Each cluster consisted of three wells screened in the three

stratigraphic units—Upper Sand Unit, Middle Fine-Grained Unit, and Lower Sand Unit.

- Use of standard methods for sampling and analysis. Disposable tubing was used to collect samples from all monitoring wells to avoid persistence of TCE in the sample tubing after sampling wells with high TCE (DNAPL) levels.

### 6.1.2 Completeness

All the regular samples planned in the QAPP were collected and analyzed, plus additional samples collected when new requirements were identified as the demonstration progressed. Additional groundwater samples were collected from all Oxidation Plot and surrounding wells to better evaluate the generation and migration of chloride, potassium ion, and potassium permanganate. One additional soil core was collected during postdemonstration sampling to evaluate the variability within the same grid cell.

All the QC samples planned in the QAPP were collected and analyzed, except for the equipment rinsate blanks during soil coring. Equipment rinsate blanks were not planned in the draft QAPP and were not collected during the predemonstration soil coring event. These blanks were later added to the QAPP and were prepared during the postdemonstration soil coring event. Based on the preliminary speed of the soil coring, one rinsate blank per day was thought to be sufficient to obtain a ratio of one blank per 20 samples (5%). However, as the speed of the soil coring increased, this frequency was found to have fallen slightly short of this ratio. The same rinsing procedure was maintained for the soil core barrel through the pre- and postdemonstration sampling. None of the blanks contained any elevated levels of CVOCs.

### 6.1.3 Chain of Custody

Chain-of-custody forms were used to track each batch of samples collected in the field and delivered either to the on-site mobile laboratory or to the off-site analytical laboratory. Copies of the chain-of-custody records can be found in Appendix G. Chain-of-custody seals were

affixed to each shipment of samples to ensure that only laboratory personnel accessed the samples while in transit. Upon arrival at the laboratory, the laboratory verified that the samples were received in good condition and the temperature blank sample sent with each shipment was measured to ensure that the required temperature was maintained during transit. Each sample received was then checked against the chain-of-custody form, and any discrepancies were brought to the attention of field personnel.

## 6.2 Field QC Measures

The field QC checks included calibration of field instruments, field blanks (5% of regular samples), field duplicates (5% of regular samples), and trip blanks; the results of these checks are discussed in this section.

Table 6-1 summarizes the instruments used for field groundwater measurements (pH, ORP, DO, temperature, water levels, and conductivity) and the associated calibration criteria. Instruments were calibrated at the beginning and end of the sampling period on each day. The field instruments were always within the acceptance criteria during the demonstration. The DO membrane was the most sensitive, especially to extremely high (near saturation) levels of chlorinated solvent or permanganate in the groundwater and this membrane had to be changed more frequently. Because of interference with DO and other measurements, field parameter measurements in deeply purple (high permanganate level) samples were avoided, as noted in Appendix G.

### 6.2.1 Field QC for Soil Sampling

Soil extractions were conducted in the field and the extract was sent to the off-site laboratory for CVOC analysis. A surrogate compound was initially planned on being spiked directly into a fraction of the soil samples collected, but the field surrogate addition was discontinued at the request of the off-site laboratory because of interference and overload of analytical instruments at the detection limits required. Surrogate addition was instead conducted by the analytical laboratory, which injected the surrogate compound into 5% of the methanol extracts

**Table 6-1.** Instruments and Calibration Acceptance Criteria Used for Field Measurements

Instrument	Measurement	Acceptance Criteria
YSI Meter Model 6820	pH	3 point, $\pm 20\%$ difference
YSI Meter Model 6820	ORP	1 point, $\pm 20\%$ difference
YSI Meter Model 6820	Conductivity	1 point, $\pm 20\%$ difference
YSI Meter Model 6820	Dissolved Oxygen	1 point, $\pm 20\%$ difference
YSI Meter Model 6820	Temperature	1 point, $\pm 20\%$ difference
Ohaus Weight Balance	Soil – Dry/Wet Weight	3 point, $\pm 20\%$ difference
Hermit Water Level Indicator	Water Levels	$\pm 0.01$ ft

prepared in the field (see Section 6.2). As an overall determination of the extraction and analytical efficiency of the soil sampling, the modified EPA 5035 methanol extraction procedure was evaluated before the demonstration by spiking a known amount of TCE into soil samples from the Launch Complex 34 aquifer. For this evaluation, soil samples from the predemonstration soil core PA-4 were homogenized and spiked with pure TCE. Replicate samples from the spiked soil were extracted and analyzed; the results are listed in Appendix G (Table G-1). For the five replicate soil samples, the TCE spike recoveries were in the range of 72 to 86%, which fell within the acceptable range (70-130%) for quality assurance of the extraction and analysis procedure.

Duplicate soil samples were collected in the field and analyzed for TCE to evaluate sampling precision. Duplicate soil samples were collected by splitting each 2-ft soil core vertically in half and subsequently collecting approximately 250 g of soil into two separate containers, marked as SB#-Depth#-A and B. Appendix G (Table G-2) shows the result of the field soil duplicate analysis and the precision, calculated as the relative percent difference (RPD) for the duplicate soil cores, which were collected before and after the demonstration. The precision of the field duplicate samples was generally within the acceptable range ( $\pm 30\%$ ) for the demonstration, indicating that the sampling procedure was representative of the soil column at the coring location. The RPD for three of the duplicate soil samples from the predemonstration sampling was greater than 30%, but less than 60%. This indicated that the repeatability of some of the predemonstration soil samples was outside targeted acceptance criteria, but within a reasonable range, given the heterogeneous nature of the contaminant distribution. The RPD for six of the duplicate soil samples from the post-demonstration sampling was greater than 30%; five of the six samples had an RPD above 60%. This indicates that the chemical oxidation treatment created greater variability in the contaminant distribution. Part of the reason for the higher RPD calculated in some postdemonstration soil samples is that TCE concentrations tended to be low (often near or below the detection limit). For example, the RPD between duplicate samples, one of which is below detection and the other is slightly above detection, tends to be high. In general, though, the variability in the two vertical halves of each 2-ft core was in a reasonable range, given the typically heterogeneous nature of the DNAPL distribution.

Field blanks for the soil sampling consisted of rinsate blank samples and methanol blank samples. The rinsate blank samples were collected once per drilling day (approximately 20 soil samples) to evaluate the decontamination efficiency of the sample barrel used for coring with the drill rigs utilized during the demonstration. Decontamination between samples consisted of a three-step

process where the core barrel was emptied, washed with soapy water, rinsed in distilled water to remove soap and debris, and then rinsed a second time with distilled water. The rinsate blank samples were collected by pouring distilled water through the sample barrel, after the barrel had been processed through the routine decontamination procedure. As seen in Appendix G (Table G-3), TCE levels in the rinsate blanks were always below detection ( $< 5.0 \mu\text{g/L}$ ), indicating that the decontamination procedure was helping control carryover of CVOCs between samples.

Methanol method blank samples (5%) were collected in the field to evaluate the soil extraction process. The results are listed in Appendix G (Table G-4). These samples were generally below the targeted detection limit of 1 mg/kg of TCE in dry soil. Detectable levels of TCE were present in methanol blanks sampled on 6/23/99 (1.8 mg/kg), 6/29/99 (8.0 mg/kg), and 7/16/99 (1.2 mg/kg) during the predemonstration phase of the project, but were still relatively low. The slightly elevated levels may be due to the fact that many of the soil samples extracted on these days were from high-DNAPL regions and contained extremely high TCE concentrations. The TCE concentrations in these blanks were below 10% of the concentrations in the associated batch of soil samples. All the postdemonstration methanol blanks were below detection.

## 6.2.2 Field QC Checks for Groundwater Sampling

QC checks for groundwater sampling included field duplicates (5%), field blanks (5%), and trip blanks. Field duplicate samples were collected once every 20 wells sampled. Appendix G (Tables G-5 and G-6) contains the analysis of the field duplicate groundwater samples that were collected before, during, and after the demonstration. The RPD (precision) calculated for these samples always met the QA/QC target criteria of  $\pm 30\%$ .

Decontamination of the sample tubing between groundwater samples initially consisted of a detergent rinse and two distilled water rinses. However, initial groundwater sampling results revealed that despite the most thorough decontamination, rinsate blanks contained elevated levels of TCE, especially following the sampling of wells containing TCE levels near or greater than its solubility (1,100 mg/L); this indicated that some free-phase solvent may have been drawn into the tubing. When TCE levels in such rinsate blanks refused to go down, even when a methanol rinse was added to the decontamination procedure, a decision was made to switch to disposable Teflon® tubing. Each new piece of tubing was used only for sampling each well once and then discarded, despite the associated costs. Once disposable sample

tubing was used, TCE levels in the rinsate blanks (Appendix G, Tables G-7 and G-8) were below the targeted detection limit (3.0 µg/L) throughout the demonstration. The only exception was one rinsate blank collected during the postdemonstration sampling event on May 20, 2000; this rinsate blank contained 11 µg/L of TCE, which was less than 10% of the TCE concentrations in the regular samples in this batch.

TCE levels in trip blank samples were always below 5 µg/L (Appendix G, Table G-9), indicating the integrity of the samples was maintained during shipment. As mentioned in Section 6.2, in some batches of groundwater samples, especially when excess permanganate was present in the sample, detection limits were raised from 3 to 5 µg/L to avoid instrument interference.

### 6.3 Laboratory QC Checks

The on-site mobile and off-site analytical laboratories performed QA/QC checks consisting of 5% matrix spikes (MS) or laboratory control spikes (LCS), as well as the same number of matrix spike duplicates (MSD) or laboratory control spike duplicates (LCSD). The analytical laboratories generally conducted MS and MSD whenever the groundwater samples were clear, in order to determine accuracy. However, when excess permanganate was present in the samples, as with many postdemonstration samplers, LCS and LCSD were conducted. MS and MSD or LCS and LCSD were used to calculate analytical accuracy (percent recovery) and precision (RPD between MS and MSD or LCS and LCSD).

#### 6.3.1 Analytical QC Checks for Soil

Analytical accuracy for the soil samples (methanol extracts) analyzed were generally within acceptance limits (70-130%) for the predemonstration period (Appendix G, Table G-10). Matrix spike recoveries were outside this range for three of the MS/MSD samples conducted during the postdemonstration sampling period (Appendix G, Table G-11), but still within 50 to 150%; this indicates that although there may have been some matrix effects, the recoveries were still within a reasonable range, given the matrix interference from the permanganate. Matrix spike recovery was 179% for one of the matrix spike repetitions on 06/01/2000. The precision between MS and MSD was always within acceptance limits ( $\pm 25\%$ ). Laboratory control spike recoveries and precision were within the acceptance criteria (Appendix G, Tables G-12 and G-13).

The laboratories conducted surrogate spikes in 5% of the total number of methanol extracts prepared from the soil samples for CVOC analysis. Table 6-2 lists the surrogate

and matrix spike compounds used by the on-site laboratory to perform the QA/QC checks. Table 6-3 lists the surrogate and matrix spike compounds used by the off-site laboratory to perform the QA/QC checks. Surrogate and matrix spike recoveries were always within the specified acceptance limits. Method blank samples were run at a frequency of at least one for every 20 samples analyzed in the pre- and postdemonstration periods (Appendix G, Tables G-14 and G-15). CVOC levels in the method blanks were always below detection.

**Table 6-2.** List of Surrogate and Matrix Spike Compounds and Their Target Recoveries for Groundwater Analysis by the On-Site Laboratory

Surrogate Compound DHL	Matrix Spike Compound DHL
a,a,a-Trifluorotoluene (75-125%)	cis-1,2-DEC (70-130%) trans-1,2-DCE (70-130%) Vinyl chloride (65-135%) TCE (70-130%)

**Table 6-3.** List of Surrogate and Laboratory Control Sample Compounds and Their Target Recoveries for Soil and Groundwater Analysis by the Off-Site Laboratory

Surrogate Compound STL	Matrix Spike Compound STL
Dibromofluoromethane (66-137%)	Vinyl chloride (56-123%)
1,2-Dichloroethane – d4 (61-138%)	Carbon tetrachloride (60-136%)
Toluene – d8 (69-132%)	Benzene (70-122%)
Bromofluorobenzene (59-145%)	1,2-Dichloroethane (58-138%)
	TCE (70-130%)
	1,2-Dichloropropane (68-125%)
	1,1,2-Trichloroethane (63-123%)
	Tetrachloroethane (70-125%)
	1,2-Dibromoethane (66-126%)
	Bromoform (60-131%)
	1,4-Dichlorobenzene (70-120%)
	cis-1,3-Dichloropropene (65-132%)

#### 6.3.2 Laboratory QC for Groundwater

Pre- and postdemonstration MS and MSD results for groundwater are listed in Appendix G (Table G-16). The MS and MSD recoveries (70 to 130%) and their precision ( $\pm 25\%$ ) were generally within acceptance criteria. The only exceptions were the samples collected on 08/03/1999 and 01/14/00 during the ongoing demonstration phase which had MS and MSD recoveries that were outside the range due to high initial TCE concentrations in the samples. Recoveries and RPDs for LCS and LCSD samples (Appendix G, Tables G-17 and G-18) were always within the acceptance range.

Method blanks (Appendix G, Tables G-19 and G-20) for the groundwater samples were always below the targeted 3- $\mu\text{g}/\text{L}$  detection limit.

### 6.3.3 Analytical Detection Limits

Detection limits for TCE in soil (1 mg/kg) and groundwater (3  $\mu\text{g}/\text{L}$ ) generally were met. The only exceptions were samples that had to be diluted for analysis, either because one of the CVOC compounds (e.g., TCE) was at a relatively high concentration as compared to another VOC compound (e.g., *cis*-1,2-DCE) or because excessively high levels of permanganate in the sample necessitated dilution to protect instruments. The proportionately higher detection limits are reported in the CVOC tables in Appendix C. The detection limits most affected were those for *cis*-1,2-DCE and vinyl chloride, due to the masking effect of high levels of TCE. Additionally, the laboratories verified and reported that analytical instrumentation calibrations were within acceptable range on the days of the analyses.

## 6.4 QA/QC Summary

Given the challenges posed by the typically heterogeneous TCE distribution in a DNAPL source zone, the collected data were a relatively good representation of the TCE distribution in the Launch Complex 34 aquifer before, during, and after the demonstration.

- Sufficient number of locations (12) were sampled within the plot to adequately capture the horizontal variability in the TCE distribution. The continuous sampling of the soil at each coring location ensured that the vertical variability of the TCE distribution was captured. Sampling and analytical procedures were appropriately modified to

address the expected variability. At the 80% confidence level, the soil sampling provided pre- and postdemonstration confidence intervals (range of TCE mass estimates) that were narrow enough to enable a good judgment of the TCE and DNAPL mass removal achieved by the chemical oxidation technology.

- Standard sampling and analysis methods were used for all other measurements to ensure that data were comparable between sampling events.
- Accuracy and precision of the soil and groundwater measurements were generally in the acceptable range for the field sampling and laboratory analysis. In the few instances that QC data were outside the targeted range, the reason was generally interference from excessive permanganate in the sample. In some cases, extremely low (near detection) or extremely high levels of TCE in the sample caused higher deviation in the precision (repeatability) of the data.
- The masking effect of high TCE levels on other CVOCs and the need for sample dilution because of the presence of excessive permanganate caused detection limits for TCE, in some cases, to rise to 5  $\mu\text{g}/\text{L}$  (instead of 3  $\mu\text{g}/\text{L}$ ). However, post-demonstration levels of dissolved TCE in many of the monitoring wells in the Oxidation Plot were considerably higher than the 3- $\mu\text{g}/\text{L}$  detection and regulatory target.
- Field blanks associated with the soil samples generally had acceptably low or undetected levels of TCE. After suitable modifications to account for the persistence of DNAPL in groundwater sampling tubing, TCE levels in field blanks were acceptably low or below detection.

## 7. Economic Analysis

The cost estimation for the chemical oxidation technology application involves the following three major components:

- Treatment cost of chemical oxidation at the demonstration site. Costs of the technology application at Launch Complex 34 were tracked by the chemical oxidation vendor and by MSE, the DOE contractor who subcontracted the vendor.
- Site preparation costs incurred by the owner. NASA and MSE tracked the site preparation costs; that is, the costs incurred by the site owner.
- Site characterization and performance assessment costs. Battelle and Tetra Tech EM, Inc. estimated these costs based on the site characterization and performance assessment that was generally based on U.S. EPA's SITE Program guidelines.

An economic analysis for an innovative technology generally is based on a comparison of the cost of the innovative technology with a conventional alternative. In this section, the economic analysis involves a comparison of the chemical oxidation cost with the cost of a conventional pump-and-treat system.

### 7.1 Chemical Oxidation Treatment Costs

The costs of the chemical oxidation technology were tracked and reported by both the vendor and MSE, the DOE contractor who subcontracted the vendor. Table 7-1 summarizes the major cost components for the application. The total cost of the chemical oxidation demonstration was approximately \$1 million. This total includes the design, permitting support, implementation, process monitoring, and reporting costs incurred by the vendor. The total does not include the costs of site characterization, which was conducted by other organizations (RI/FS study by NASA, preliminary characterization by WSRC, and detailed characterization by Battelle/Tetra Tech EM, Inc./U.S. EPA). The vendor estimated that approximately 15 to 20% of the total cost was demonstration-related

**Table 7-1. Chemical Oxidation Cost Summary Provided by Vendor**

Item	Actual Cost
Final design and specifications	\$ 48,301
Plans and permits	\$ 23,367
Procurement	\$ 15,696
Mobilization <sup>(a)</sup>	\$ 410,412
Well installation	\$ 46,675
Precharacterization sampling	\$ 3,292
Tracer test	\$ 48,846
Phase 1 injection and monitoring	\$ 124,883
Phase 2 injection and monitoring	\$ 38,737
Phase 3 injection and monitoring	\$ 104,566
Process monitoring	\$ 1,554
Cost reporting	\$ 24,270
Design/cost modeling	\$ 9,919
Final technical report	\$ 49,161
Project management/proposal	\$ 64,268
Total	\$1,013,947

(a) Mobilization includes chemical costs for permanganate and major project equipment rentals and purchases.

Source: IT Corporation, 2000.

and would not be incurred in an actual remediation application.

### 7.2 Site Preparation Costs

Many of the site preparation costs were incurred by NASA and are not included in the treatment costs listed by the vendor in Table 7-1. Site preparation costs for the chemical oxidation technology were relatively minor, compared to the other two technologies demonstrated. For chemical oxidation, site preparation involved the provision of power and water for the demonstration. NASA estimated the site preparation costs at \$2,800. NASA did not incur any waste disposal costs associated with this technology because injected fluids did not have to be extracted. Except for the disposal of some mobilization- and operation-related nonhazardous solid wastes, there was no waste disposal requirement.

## 7.3 Site Characterization and Performance Assessment Costs

This section describes two categories of costs:

- Site characterization costs. These are the costs that a site would incur in an effort to bridge the gap between the general site information in an RI/FS or RFI report and the more detailed information required for DNAPL source delineation and remediation technology design. This cost component is perhaps the most reflective of the type of costs incurred when a site of the size and geology of Launch Complex 34 undergoes site characterization in preparation for remediation. Presuming that groundwater monitoring and plume delineation at a site indicates the presence of DNAPL, these site characterization costs are incurred in an effort to define the boundaries of the DNAPL source zone, obtain an order-of-magnitude estimate of the DNAPL mass present, and define the local hydrogeology and geochemistry of the DNAPL source zone.
- Performance assessment costs. These are primarily demonstration-related costs. Most of these costs were incurred in an effort to further delineate the portion of the DNAPL source contained in the Oxidation Plot and determine the TCE/DNAPL mass removal achieved by chemical oxidation. Only a fraction of these costs would be incurred during full-scale deployment of this technology; depending on the site-specific regulatory requirements, only the costs related to determining compliance with cleanup criteria would be incurred in a full-scale deployment.

Table 7-2 summarizes the costs incurred by Battelle for the February 1999 site characterization. The February 1999 site characterization event was a suitable combination of soil coring and groundwater sampling, organic and inorganic analysis, and hydraulic testing (water levels and slug tests) that may be expected to bridge the gap between the RI/FS or RFI data usually available at a site and the typical data needs for DNAPL source delineation and remediation design.

Performance assessment costs incurred jointly by Battelle and Tetra Tech EM, Inc. are listed in Table 7-3.

## 7.4 Present Value Analysis of Chemical Oxidation and Pump-and-Treat System Costs

DNAPL, especially of the magnitude present at Launch Complex 34, is likely to persist in the aquifer for several

**Table 7-2. Estimated Site Characterization Costs**

Activity	Cost
Site Characterization Work Plan	\$ 25,000
• Additional characterization to delineate DNAPL source	
• Collect hydrogeologic and geochemical data for technology design	
Site Characterization	\$ 165,000
• Drilling – soil coring and well installation (12 continuous soil cores to 45 ft bgs; installation of 36 monitoring wells)	
• Soil and groundwater sampling (36 monitoring wells; 300 soil samples collection and field extraction)	
• Laboratory analysis (organic and inorganic analysis)	
• Field Measurements (water quality; hydraulic testing)	
Data Analysis and Site Characterization Report	\$ 65,000
Total	<b>\$ 255,000</b>

**Table 7-3. Estimated Performance Assessment Costs**

Activity	Cost
Predemonstration Assessment	\$208,000
• Drilling – 12 continuous soil cores, installation of 18 monitoring wells	
• Soil and groundwater sampling for TCE/DNAPL boundary and mass estimation (36 monitoring wells; 300 soil samples collection and field extraction)	
• Laboratory analysis (organic and inorganic analysis)	
• Field measurements (water quality; hydraulic testing)	
Demonstration Assessment	\$240,000
• Groundwater sampling (Oxidation Plot and perimeter wells)	
• Laboratory analysis (organic and inorganic analysis)	
• Field measurements (water quality; hydraulic testing; Oxidation Plot and perimeter wells)	
Postdemonstration Assessment	\$215,000
• Drilling – 12 continuous soil cores, installation of 18 monitoring wells	
• Soil and groundwater sampling (36 monitoring wells; 300 soil samples collection and field extraction)	
• Laboratory analysis (organic and inorganic analysis)	
• Field measurements (water quality; hydraulic testing)	
Total	<b>\$ 663,000</b>

decades or centuries. The resulting groundwater contamination and plume will also persist for several decades. The conventional approach to this type of contamination has been the use of pump-and-treat systems that extract and treat the groundwater above ground. This

conventional technology is basically a plume control technology and would have to be implemented as long as groundwater contamination exists. Chemical oxidation is an innovative in situ technology that seeks to replace the conventional pump-and-treat approach. The economic analysis therefore compares the costs of these two alternatives.

Because a pump-and-treat system would have to be operated for the next several decades, the life-cycle cost of this long-term treatment has to be calculated and compared with the cost of chemical oxidation, a short-term treatment. The present value (PV) of a long-term pump-and-treat application is calculated as described in Appendix H. The PV analysis is conducted over a 30-year period, as is typical for long-term remediation programs at Superfund sites. Site characterization and performance (compliance) assessment costs are assumed to be the same for both alternatives and are not included in this analysis.

For the purpose of comparison, it is assumed that a pump-and-treat system would have to treat the plume emanating from a DNAPL source the size of the Oxidation Plot. Recent research (Pankow and Cherry, 1996) indicates that the most efficient pump-and-treat system for source containment would capture all the groundwater flowing through the DNAPL source region. For a 75-ft-long  $\times$  50-ft-wide  $\times$  40-ft-deep DNAPL source region at Launch Complex 34, a single extraction well pumping at 2 gpm is assumed to be sufficient to contain the source in an aquifer where the hydraulic gradient (and therefore, the groundwater flow velocity) is extremely low. This type of minimal containment pumping ensures that the source is contained without having to extract and treat groundwater from cleaner surrounding regions, as would be the case in more aggressive conventional pump-and-treat systems. The extracted groundwater is treated with an air stripper and polishing carbon. The air effluent from the air stripper is assumed to be within allowable limits for VOCs and is discharged directly without further treatment.

As shown in Appendix H, the total capital investment for an equivalent pump-and-treat system would be approximately \$102,000, and would be followed by an annual operation and maintenance (O&M) cost of \$44,000 (including quarterly monitoring). Periodic maintenance requirements (replacements of pumps, etc.) would raise the O&M cost every five years to \$52,000 and every 10 years to \$64,000. A discount rate of 2.9%, based on the current recommendation for government projects,

was used to calculate the PV. The PV of the pump-and-treat costs over 30 years is estimated to be **\$1,032,000**.

Based on the vendor's assessment that 15% of the total treatment cost for the Oxidation Plot was demonstration-related, an equivalent treatment cost for full-scale deployment of the chemical oxidation technology would be approximately \$850,000. This estimate is based on a total treatment and site preparation cost during the demonstration of approximatley \$1 million (from Table 7-1 and Section 7-2), less 15% of demonstration-related monitoring costs. Therefore, if the TCE remaining in the Oxidation Plot was allowed to attenuate naturally, the total treatment cost of chemical oxidation would be around **\$850,000**.

The economics of the chemical oxidation technology compare favorably with the economics of an equivalent pump-and-treat system. As seen in Table H-3 in Appendix H, an investment in chemical oxidation would be recovered in the 22nd year, when the PV of a pump-and-treat system exceeds the cost of chemical oxidation. In addition to lower PV or life-cycle costs, there may be other tangible and intangible economic benefits to using a source remediation technology that are not factored into the analysis. For example, the economic analysis in Appendix H assumes that the pump-and-treat system is operational all the time over the next 30 or more years, with most of the annual expense associated with operation and routine (scheduled) maintenance. Experience with pump-and-treat systems at several sites has shown that downtime associated with pump-and-treat systems is fairly high (as much as 50% downtime reported from some sites). This may negatively impact both maintenance requirements (tangible cost) and the integrity of plume containment (intangible cost) with the pump-and-treat alternative.

Another factor to consider is that although the economic analysis for long-term remediation programs typically is conducted for a 30-year period, the DNAPL source and therefore the pump-and-treat requirement, may persist for many more years or decades. This would lead to concomitantly higher remediation costs for plume containment (without source removal). Even if the limitations on the effectiveness of a source removal technology at some sites necessitate the use of pump-and-treat for the next few years, until the source (and plume) is further depleted, the size of the pump-and-treat system and the time period over which it needs to be operated is likely to be considerably reduced.

## 8. Technology Applications Analysis

This section evaluates the general applicability of the chemical oxidation technology to sites with contaminated groundwater and soil. The analysis is based on the results and lessons learned from the IDC demonstration, as well as general information available about the technology and its application at other sites.

### 8.1 Objectives

This section evaluates the chemical oxidation technology against the nine evaluation criteria used for detailed analysis of remedial alternatives in feasibility studies under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Much of the discussion in this section applies to DNAPL source removal in general, and chemical oxidation in particular. Here chemical oxidation refers to the mode in which this technology was applied at Launch Complex 34 — namely, by injection of industrial-grade potassium permanganate solution without concomitant extraction.

#### 8.1.1 Overall Protection of Human Health and the Environment

Chemical oxidation is protective of human health and environment in both the short and long term. At Launch Complex 34 for example, chemical oxidation removed more than 4,000 kg of DNAPL contamination from the Oxidation Plot, with significant TCE mass destruction by oxidation. Because DNAPL acts as a secondary source that can contaminate an aquifer for decades or centuries, DNAPL source removal or mitigation considerably reduces the duration over which the source is active. Even if DNAPL mass removal is not 100%, the resulting long-term weakening of the plume and the reduced duration over which the DNAPL source contributes to the plume reduces the threat to potential receptors.

#### 8.1.2 Compliance with ARARs

This section describes the technology performance versus applicable or relevant and appropriate requirements

(ARARs). Compliance with chemical-, location-, and action-specific ARARs should be determined on a site-specific basis. Generally, location- and action-specific ARARs can be met with this technology, especially because of the following reasons:

- Injected oxidant solution is not reextracted or reinjected; therefore, there are no aboveground residuals that need treatment or disposal.
- When permanganate is used as the oxidant, there are no exothermic reactions that generate heat, and, therefore, no potential releases to the atmosphere.

Compliance with chemical-specific ARARs depends on the efficiency of the chemical oxidation process at the site and the cleanup goals agreed on by various stakeholders. In general, reasonable DNAPL mass removal goals are more achievable and should lead to eventual and earlier compliance with long-term groundwater cleanup goals. Achieving short-term groundwater cleanup goals (e.g., federal or state maximum contaminant levels [MCLs]), especially in the DNAPL source zone, is more difficult because various studies (Pankow and Cherry, 1996) have shown that almost 100% DNAPL mass removal may be required before a significant change in groundwater concentrations is observed. However, removal of DNAPL, even if most of the removal takes place from the more accessible pores, would probably result in a weakened plume that may allow risk-based cleanup goals to be met in the downgradient aquifer.

The specific federal environmental regulations that are potentially impacted by remediation of a DNAPL source with chemical oxidation are described below.

#### 8.1.2.1 Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)

CERCLA, as amended by the Superfund Amendments and Reauthorization Act (SARA), provides for federal authority to respond to releases or potential releases of any hazardous substance into the environment, as well

as to releases of pollutants or contaminants that may present an imminent or significant danger to public health and welfare or the environment. Remedial alternatives that significantly reduce the volume, toxicity, or mobility of hazardous materials and that provide long-term protection are preferred. Selected remedies must also be cost-effective and protective of human health and the environment. The chemical oxidation technology meets several of these criteria relating to a preferred alternative. Chemical oxidation reduces the toxicity of oxidizable contaminants by converting them into potentially nontoxic forms. For example, at Launch Complex 34, as described in Section 5.3.1, the hazardous chlorinated solvent TCE was converted to carbon dioxide, chloride, and water, without generating any aboveground residuals. This elimination of solvent hazard is permanent and leads to a considerable reduction in the time it takes for the DNAPL source to deplete fully. Although aquifer heterogeneities and technology limitations often result in less than 100% removal of the contaminant and elevated levels of dissolved solvent may persist in the groundwater over the short term, in the long term, there is faster and eventual elimination of groundwater contamination. Section 7.4 shows that chemical oxidation is cost-effective compared with the conventional alternative of long-term pump and treat.

#### **8.1.2.2 Resource Conservation and Recovery Act (RCRA)**

RCRA, as amended by the Hazardous and Solid Waste Amendments (HSWA) of 1984, regulates management and disposal of municipal and industrial solid wastes. The U.S. EPA and RCRA-authorized states (listed in 40 CFR part 272) implement and enforce RCRA and state regulations. Generally, RCRA does not apply to in situ groundwater treatment because the contaminated groundwater may not be considered hazardous waste while it is still in the aquifer. The contaminated groundwater becomes regulated if it is extracted from the ground, as would happen with the conventional alternative of pump and treat. At least in the injection-only (no extraction) mode implemented at Launch Complex 34, no aboveground waste streams that may be hazardous, as defined by RCRA, are generated. At some sites, where hydraulic control requirements necessitate extraction and reinjection or treatment/disposal of injected fluids, RCRA may be invoked.

#### **8.1.2.3 Clean Water Act (CWA)**

The CWA is designed to restore and maintain the chemical, physical, and biological quality of navigable surface waters by establishing federal, state, and local discharge standards. In the injection-only mode adopted at Launch Complex 34, there was no extraction of groundwater and therefore no reinjection or treatment/disposal of water; in

this mode, the CWA may not be triggered. If, however, groundwater extraction is conducted in conjunction with injection, and the resulting water stream needs to be treated and discharged to a surface water body or a publicly owned treatment works (POTW), the CWA may apply. On-site discharges to a surface water body must meet National Pollutant Discharge Elimination System (NPDES) requirements, but may not require an NPDES permit. Off-site discharges to a surface water body must meet NPDES limits and require an NPDES permit. Discharge to a POTW, even if it is through an on-site sewer, is considered an off-site activity. Sometimes, soil or groundwater monitoring may lead to small amounts of purge and decontamination water wastes that may be subject to CWA requirements. Micropurging was one measure implemented at Launch Complex 34 to minimize such wastes during site characterization and technology performance assessment.

#### **8.1.2.4 Safe Drinking Water Act (SDWA)**

The SDWA, as amended in 1986, requires U.S. EPA to establish regulations to protect human health from contaminants in drinking water. The legislation authorizes national drinking water standards and a joint federal-state system for ensuring compliance with these standards. The SDWA also regulates underground injection of fluids and includes sole-source aquifer and wellhead protection programs.

The National Primary Drinking Water Standards are found at 40 CFR Parts 141 through 149. The health-based SDWA primary standards (e.g., for TCE) are more critical to meet; SDWA secondary standards (e.g., for dissolved manganese) are based on other factors, such as aesthetics (discoloration) or odor. The MCLs based on these standards generally apply as cleanup standards for water that is, or potentially could be, used for drinking water supply. In some cases, such as when multiple contaminants are present, alternative concentration limits (ACL) may be used. CERCLA and RCRA standards and guidance are used in establishing ACLs. In addition, some states may set more stringent standards for specific contaminants. For example, the federally mandated MCL for vinyl chloride is 2 µg/L, whereas the State of Florida drinking water standard is 1 µg/L. In such instances, the more stringent standard is usually the cleanup goal.

Although the long-term goal of DNAPL source zone treatment is meeting applicable drinking water standards or other risk-based groundwater cleanup goals agreed on between site owners and regulatory authorities, the short-term objective of chemical oxidation and source remediation is DNAPL mass removal. Because technology, site, and economic limitations may limit DNAPL mass removal to less than 100%, it may not always be

possible to meet groundwater cleanup targets in the source region in the short term. Depending on other factors, such as the distance of the compliance point (e.g., property boundary, at which groundwater cleanup targets have to be met) from the source (as negotiated between the site owner and regulators), the degree of weakening of the plume due to DNAPL source treatment, and the degree of natural attenuation in the aquifer, it may be possible to meet groundwater cleanup targets at the compliance point in the short term. DNAPL mass removal will always lead to faster attainment of groundwater cleanup goals in the long term, as compared to the condition in which no source removal action is taken.

One aspect of using potassium permanganate solution as an oxidant for DNAPL source remediation is the presence of regulated trace metals in industrial-grade permanganate, the grade that is most commonly and economically available commercially. Depending on the concentration of permanganate used, levels of trace metals in the injected solution and/or the treated aquifer may exceed federal or state drinking water standards. At Launch Complex 34, injection of a 1 to 2% solution of permanganate resulted in elevated levels of some trace metals in the aquifer during and immediately after the demonstration (see Section 5.2.2). There is also the possibility that the strong oxidant may cause the release of other regulated metals (e.g., iron) from the aquifer formation or from other underground structures. Dissolved manganese originating from the oxidant is also subject to secondary drinking water standards.

Elevated levels of these metals of concern are expected to subside over time; the time period required for the metals to once again meet applicable drinking water standards will depend on the groundwater flux through the treated zone, once normal flow resumes. Many of the elevated metals are subject to secondary drinking water standards, which are somewhat less of a concern than target contamination (DNAPL) and metals subject to primary standards. One option for mitigating these concerns is to use the more expensive pharmaceutical grade. Another option is to reduce the concentration of industrial-grade permanganate in the injected solution to a level where trace metal concentrations are compatible with regulatory standards applicable to the injected solution and/or the treated aquifer. The tradeoff between higher injected permanganate concentration (lower injection volumes and times) and lower injected permanganate (higher injection volumes and times) should be taken into consideration on a site-by-site basis.

#### **8.1.2.5 Clean Air Act (CAA)**

The CAA and the 1990 amendments establish primary and secondary ambient air quality standards for protec-

tion of public health, as well as emission limitations for certain hazardous pollutants. Permitting requirements under CAA are administered by each state as part of State Implementation Plans (SIP) developed to bring each state in compliance with National Ambient Air Quality Standards (NAAQS).

Unlike pump-and-treat systems, which often generate air emissions (when an air stripper is used), and unlike other source removal technologies that use thermal energy (e.g., steam injection or resistive heating) or result in exothermic reactions (e.g., oxidation with Fenton's reagent), the potential for atmospheric releases by chemical oxidation with potassium permanganate is absent. Surface emission tests conducted in the Oxidation Plot during and after the demonstration did not show any TCE emissions above background levels.

#### **8.1.2.6 Occupational Safety and Health Administration (OSHA)**

CERCLA remedial actions and RCRA corrective actions must be carried out in accordance with OSHA requirements detailed in 20 CFR Parts 1900 through 1926, especially Part 1910.120, which provide for the health and safety of workers at hazardous waste sites. On-site construction activities at Superfund or RCRA corrective action sites must be performed in accordance with Part 1926 of RCRA, which provides safety and health regulations for construction sites. State OSHA requirements, which may be significantly stricter than federal standards, must also be met.

The health and safety aspects of chemical oxidation are minimal, and are described in Section 3.3, which describes the operation of this technology at Launch Complex 34. Level D personal protective equipment generally is sufficient during implementation. Operation of heavy equipment and handling of a strong oxidant are the main working hazards and are dealt with by using appropriate PPE and trained workers. All operating and sampling personnel are required to have completed the 40-hour HAZWOPER training course and 8-hour Refreshers.

#### **8.1.3 Long-Term Effectiveness and Permanence**

Chemical oxidation leads to destruction of DNAPL mass and therefore permanent removal of contamination from the aquifer. Although dissolved solvent concentrations may rebound in the short-term when groundwater flow redistributes through the treated source zone containing DNAPL remnants, in the long-term, depletion of the source through dissolution will continue and lead to eventual and earlier compliance with groundwater cleanup goals.

### **8.1.4 Reduction of Toxicity, Mobility, or Volume through Treatment**

Chemical oxidation effects treatment by reducing the toxicity of the contamination. Hazardous chlorinated solvents or other target contaminants are oxidized to potentially nontoxic compounds, such as chloride, carbon dioxide, and water.

### **8.1.5 Short-Term Effectiveness**

Short-term effectiveness of the chemical oxidation technology depends on a number of factors. If the short-term goal is to remove as much DNAPL mass as possible, this goal is likely to be met. If the short-term goal is to reduce dissolved contaminant levels in the source zone, achievement of this goal will depend on the hydrogeology and DNAPL distribution in the treated region. As seen in Section 5.2.1, TCE levels declined sharply in some monitoring wells in the Oxidation Plot, but rose in one of the wells. Geologic heterogeneities, preferential flowpaths taken by the oxidant, and localized permeability changes that determine flow in the treated region may lead to such variability in posttreatment groundwater levels of contamination. As discussed in Section 8.1.2.4, the chances of DNAPL mass removal resulting in reduced contaminant levels at a compliance point downgradient from the source is more likely in the short term. In the long term, DNAPL mass removal will always shorten the time period required to bring the entire affected aquifer in compliance with applicable standards.

### **8.1.6 Implementability**

As mentioned in Section 7.2, site preparation and access requirements for implementing chemical oxidation are minimal. Firm ground for set up of the permanganate storage and mixing equipment is required. The equipment and chemicals involved are commercially available. Setup and shakedown times are relatively small. Overhead space available at open sites is generally sufficient for housing storage and GeoProbe® equipment, if required. Accessibility to the portion of the contamination under the Engineering Service Building at Launch Complex 34 was not particularly good with normal injection from the outside. The use of angled injection wells/drive points or the capability of conducting injection from inside the building may be required to remediate more of the contamination under the building.

Generally, 8 to 10 hours of operator attention each day is sufficient to keep the oxidant flowing through the injection points and 24-hour presence is not required, as long as the system is automated enough that it shuts off when any backpressure is sensed in the injection lines. Strong oxidant and byproduct colors make it easier to

track the progress of the oxidant in the aquifer, although confirmatory groundwater and soil sampling is required. The strong oxidant is a chemical hazard, but one that can be handled through the use of basic personal protective equipment and a common neutralizing solution.

At least in the injection-only mode used at Launch Complex 34, chemical oxidation did not generate any significant aboveground wastes that required treatment and reinjection/disposal. If additional hydraulic control is to be achieved through the use of strategic extraction wells, then the complexity of the operation may increase to some degree and waste generation and handling requirements may become significant.

### **8.1.7 Cost**

As described in Section 7.4, the cost of the chemical oxidation treatment is competitive with the life-cycle cost of pump and treat (over a 30-year period of comparison). The cost comparison becomes even more favorable for source remediation in general and chemical oxidation in particular when other tangible and intangible factors are taken into account. For example, a DNAPL source, such as the one at Launch Complex 34, is likely to persist much longer than 30 years (the normal evaluation time for long-term remedies), thus necessitating continued costs for pump and treat into the distant future (perhaps 100 years or more). Annual O&M costs also do not take into account the nonroutine maintenance costs associated with the large amount of downtime typically experienced by site owners with pump-and-treat systems.

Factors that may increase the cost of the chemical oxidation application are:

- Operating requirements associated with any contamination under a building
- Stringent regulatory requirements on elevated levels of trace metals in the treated aquifer that necessitate operating longer with lower permanganate concentrations or moving to a higher grade of oxidant.
- Need for additional hydraulic control (e.g., with extraction wells) and any associated need to treat and dispose/reinject extracted fluids.

### **8.1.8 State Acceptance**

The ITRC, a consortium of several states in the United States, is participating in the IDC demonstration through reports review and attendance at key meetings. The ITRC plays a key role in innovative technology transfer by helping disseminate performance information and regulatory guidance to the states.

The IDC set up a partnering team consisting of representatives from NASA and Patrick AFB (site owners), U.S. EPA, State of Florida Department of Environmental Protection (FDEP), and other stakeholders early on when the demonstration was being planned. The partnering team was and is being used as the mechanism to proactively obtain regulatory input in the design and implementation of the remediation/demonstration activities at Launch Complex 34. Because of the technical limitations and costs of conventional approaches to DNAPL remediation, state environmental agencies have shown growing acceptance of innovative technologies.

### **8.1.9 Community Acceptance**

The chemical oxidation technology's low profile, limited space requirements, absence of air emissions, absence of waste storage, handling, and off-site transportation requirements, low noise levels, and ability to reduce short- and long-term risks posed by DNAPL contamination are expected to promote local community acceptance.

## **8.2 Operability**

Unlike a pump-and-treat system that may involve continuous long-term operation by trained operators for the next 30 or 100 years, a source remediation technology is a short-term application. The field application of chemical oxidation in the 75-ft × 50-ft plot at Launch Complex 34 took about seven months to complete. The remediation generally is done as a turnkey project by multiple vendors, who will design, build, and operate the oxidant delivery system. Site characterization, site preparation (utilities, etc.), monitoring, and any waste disposal often are done by the site owner. Although some aspects of the process may be patented, chemical oxidation of dissolved contamination, in general, has been known for a long time and is commercially available.

The chemical (permanganate) oxidation process is relatively easy to set up and operate using off-the-shelf equipment and generally proficient operators. Potassium permanganate handling requires moderate health and safety measures; however, other oxidants, such as Fenton's reagent or ozone, may require additional precautions.

## **8.3 Applicable Wastes**

Chemical oxidation has primarily been applied to remediation of aquifers contaminated with chlorinated solvents. Source zones consisting of PCE and TCE in DNAPL form, as well as dissolved *cis*-1,2 DCE and vinyl chloride can be addressed. However, oxidation has a range of other potential applications. Permanganate, for example, is able to oxidize source zones containing naphthalene, phenanthrene, pyrene, and phenols. Chemical oxidation

can be implemented in source zones present in saturated or vadose zones. The technology also has been contemplated for treating dissolved contaminant plumes of these compounds. Oxidants, such as Fenton's reagent, have been found to be capable of treating MTBE hot spots. In general, any contaminant that exists in a relatively reduced form that can be oxidized into potentially nontoxic products is amenable for treatment by chemical oxidation.

## **8.4 Key Features**

The following are some of the key features of chemical (permanganate) oxidation that makes it attractive for DNAPL source zone and groundwater treatment:

- In situ application
- Potential for injection-only mode at some sites that prevents the generation of aboveground wastes, which would need additional treatment or handling
- Potentially nontoxic products
- Uses relatively simple, commercially available equipment
- Relatively fast field application time
- Longer-lived oxidant (potassium permanganate) distributes in the aquifer through both advection and diffusion, thus achieving better contact with contaminants
- At many sites, a one-time application has the potential to reduce a DNAPL source to the point where either natural attenuation is sufficient to address a weakened plume or pump and treat needs to be applied for over a shorter duration in the future.

## **8.5 Availability/Transportability**

Chemical oxidation is commercially available from multiple vendors or consulting organizations as a service on a contract basis. In addition, potassium permanganate or sodium permanganate suppliers are familiar enough with the application that they can help design some of the front-end permanganate storage and delivery equipment. No stand-alone mobile chemical oxidation plant has been built, but components are readily available and oxidant delivery systems can be assembled or disassembled on site relatively quickly.

## **8.6 Materials Handling Requirements**

Potassium permanganate is typically available as a solid and requires solids handling and mixing equipment;

however, sodium permanganate is available as a solution that can be diluted on site before the in situ application.

## 8.7 Ranges of Suitable Site Characteristics

The following factors should be considered when determining the suitability of a site for chemical oxidation application:

- **Type of contaminants.** Contaminants should be amenable to oxidation with commonly available oxidants.
- **Site geology.** Oxidant can be distributed more effectively in sandy soils. Silts or clays can make the application more difficult. Aquifer heterogeneities and preferential flowpaths can make contact between the oxidant and the contaminants more difficult. DNAPL source zones in fractured bedrock also may pose a challenge.
- **Soil characteristics.** Soils with low organic carbon content require less oxidant and application is relatively quicker. Soils with higher organic content consume more oxidant and slow down the spread of the oxidation front.
- **Regulatory acceptance.** Although chemical oxidation has long-term benefits in terms of a diminished DNAPL source, at least in the short term, use of industrial-grade permanganate can elevate the levels of trace metals in the treated aquifer. Regulatory acceptance is important for this application. In addition, hydraulic control requirements and economics at some sites may necessitate extraction, treatment, and reinjection of the oxidant solution. A reinjection permit will be required.

- **Site accessibility.** Sites that have no above-ground structures and fewer utilities are easier to remediate with chemical oxidation. Presence of buildings or a network of utilities can make the application more difficult.

None of the factors mentioned above necessarily eliminate chemical oxidation from consideration. Rather, these are factors that may make the application less or more economical.

## 8.8 Limitations

The chemical oxidation technology has the following limitations:

- Not all types of contaminants are amenable to oxidative transformation. In addition, some co-contaminants, such as heavy metals, could be mobilized by oxidation.
- Byproducts of oxidation may make it unsuitable for application in a region close to a receptor, even though many of these byproducts are subject to secondary (nonhealth-based) drinking water standards. Byproducts, such as manganese, chloride, and trace metals, require sufficient time and distance to dissipate.
- Aquifer heterogeneities can make the application more difficult, necessitating more complex application schemes, greater amounts of oxidant, and/or longer injection times.
- Some sites may require greater hydraulic control to minimize the spread of contaminants. This may necessitate the use of extraction, aboveground treatment, and disposal/reinjection.

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## **Appendix A. Performance Assessment Methods**

- A.1 Statistical Design and Data Analysis Methods
- A.2 Sample Collection and Extraction Methods
- A.3 List of Standard Sample Collection and Analytical Methods

## A.1 Statistical Design and Data Analysis Methods

Estimating TCE/DNAPL mass removal due to the chemical oxidation technology application was a critical objective of the IDC demonstration at Launch Complex 34. Analysis of TCE in soil samples collected in the Oxidation Plot before and after the demonstration was the main tool used to make a determination of the mass removal. Soil sampling was used to obtain pre- and postdemonstration data on the TCE distribution in the Oxidation Plot. Three data evaluation methods were used for estimating TCE/DNAPL masses in the Oxidation Plot before and after the demonstration:

- Contouring
- Kriging
- Pairwise comparison.

Section 4.1 (in Section 4.0 of the report) contains a general description of these three methods. Section 5.1 (in Section 5.0 of this report) summarizes the results.

The *contouring* method is the most straightforward and involves determining TCE concentrations at unsampled points in the plot by linear interpolation (estimation) of the TCE concentrations between sampled points. The contouring software EarthVision™ uses the same methodology that is used for drawing water level contour maps based on water level measurements at discrete locations in a region. The only difference with this software is that the TCE concentrations are mapped in three dimensions to generate iso-concentration shells. The TCE concentration in each shell is multiplied by the volume of the shell (as estimated by the software) and the bulk density of the soil (1.59 g/cc, estimated during preliminary site characterization) to estimate a mass for each shell. The TCE mass in each region of interest (Upper Sand Unit, Middle-Fine-Grained Unit, Lower Sand Unit, and the entire plot) is obtained by adding up the portion of the shells contained in that region. The DNAPL mass is obtained by adding up the masses in only those shells that have TCE concentrations above 300 mg/kg. Contouring provides a single mass estimate for the region of interest.

The contouring method relies on a high sampling density (collecting a large number of samples in the test plot) to account for any spatial variability in the TCE concentration distribution. By collecting around 300 samples in the plot during each event (before and after treatment) the expectation is that sufficient coverage of the plot has been obtained to make a reliable determination of the true TCE mass in the region of interest. Section A.1.1 of this appendix describes how the number of samples and appropriate sampling locations were determined to obtain good coverage of the 75 ft x 50 ft plot.

Kriging and pairwise comparison are two statistical techniques that go beyond the contouring method described above and addresses the spatial variability of the TCE distribution by taking into account the uncertainties associated with interpolating between sampled points. Unlike contouring, which provides a single mass estimate, both Kriging and pairwise comparison provide a range of estimated values that take into account the uncertainties (variability) in the region of interest. In this appendix, Section A.1.2 describes the kriging approach and results. Section A.1.3 describes the pairwise comparison approach and results.

### A.1.1 Sampling Design to Obtain Sufficient Coverage of the Oxidation Plot

Selection of the sampling plan for this particular test plot was based, in part, on the objectives of the study for which the samples were being collected. In this study, the objectives were:

- Primary objective:** To determine the magnitude of the reduction in the levels of TCE across the entire test plot.
- Secondary objectives:**
- To determine whether remediation effectiveness differs by depth (or stratigraphic unit such as the upper sand unit [USU], middle fine-grained unit [MFGU], or lower sand unit [LSU]).
- To determine whether the three remediation technologies demonstrated differ in their effectiveness at removing chlorinated volatile organic compounds (CVOCs).

Four alternative plans for selecting the number and location of sampling in the test plot were examined. These four plans were designated as simple random sampling (SRS), paired sampling, stratified sampling, and systematic sampling. Each plan is discussed in brief detail below.

#### Simple Random Sampling

The most basic statistical sampling plan is SRS, in which all locations within a given sampling region are equally likely to be chosen for sampling. For this study, using SRS would require developing separate SRS plans for each of the three test plots. In addition, because two sampling events were planned for the test plot, using SRS would involve determining two sets of unrelated sampling locations for the test plot.

The main benefit of using SRS is that the appropriate sample size can be determined easily based on the required power to detect a specific decrease in contaminant levels. In addition, SRS usually involves a reasonable number of samples. However, a key disadvantage of using SRS is that it would not guarantee complete coverage of the test plot; also, if contaminant levels are spatially correlated, SRS is not the most efficient sampling design available.

#### Paired Sampling

Paired sampling builds on SRS methods to generate one set of paired sampling locations for a given test plot rather than two separate sets. Instead of sampling from each of two separate random sample locations for pre- and post-remediation sampling, paired sampling involves the positioning of post-remediation sample locations near the locations of pre-remediation sampling. The number of samples required to meet specific power and difference requirements when using this design would be similar to the number of locations involved using SRS; the exact sample size cannot be determined because information is required about contaminant levels at collocated sites before and after remediation.

Paired sampling offers three significant benefits to this particular study. First, the work of determining the sampling locations is reduced in half. Second, the comparison of contaminant levels before and after remediation is based on the differences in levels at collocated sites. Third, the variability of the difference should be less than the variability associated with the SRS, which would result in a more accurate test. The disadvantages of this sampling procedure are the same as with the SRS: there is no guarantee of complete coverage of the test plot, and the plan is inefficient for spatially correlated data.

### **Stratified Sampling**

Stratified sampling guarantees better coverage of the plot than either SRS or paired sampling: to ensure complete coverage of a given test plot, it is divided into a regular grid of cells, and random samples are drawn from each of the grid cells. Samples then are selected within each grid cell either using SRS or paired sampling. The number of samples required to meet specific power and difference requirements would be slightly greater than that for SRS, although the difference would not be great. For this study, which involves test plots 50 × 75 ft in size, the most effective grid size would be 25 × 25 ft, which results in six grid cells per test plot.

Again, the main benefit of stratified sampling is that it guarantees more complete coverage of the test plot than SRS or paired sampling. Also, if any systematic differences in contaminant levels exist across the site, stratified sampling allows for separate inferences by sub-plot (i.e., grid cell). Disadvantages of stratified sampling are that the method requires a slightly larger number of samples than SRS or paired sampling methods, and that stratified sampling performs poorly when contaminant levels are spatially correlated.

### **Systematic Sampling**

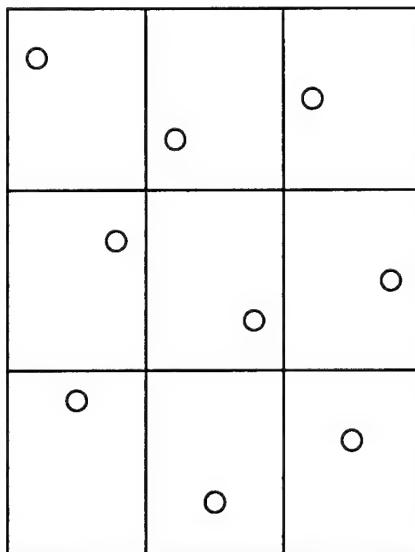
The samples for the oxidation demonstration were collected using a systematic sampling plan. Systematic sampling is the term applied to plans where samples are located in a regular pattern. In geographic applications such as this study, the systematic sampling method involves the positioning of sampling locations at the nodes of a regular grid. The grid need not be square or rectangular; in fact, a grid of equilateral triangles is the most efficient grid design. (Regular hexagonal grids also have been used regularly and are nearly as efficient as triangles and squares.) The number of samples and the size of the area to be sampled determine the dimensions of the grid to be used. With systematic sampling, the selection of initial (e.g., pre-remediation) set of sampling locations requires the random location of only one grid node, because all other grid nodes will be determined based on the required size of the grid and the position of that first node. A second (e.g., post-remediation) set of sampling locations can be either chosen using a different random placement of the grid or collocated with the initial set of sampling locations.

One variation of the systematic sampling method worth consideration is *unaligned* sampling. Under this method, a given test plot is divided into a grid with an equal number of rows and columns. One sample per grid cell then is selected by:

- Assigning random horizontal coordinates for each row of the grid;
- Assigning random vertical coordinates for each column of the grid;
- Determining the sampling locations for a cell by using the horizontal and vertical coordinates selected for the corresponding row and column.

In other words, every cell in a row shares a horizontal coordinate, and every cell in a column shares a vertical coordinate. Figure A-1 illustrates the locations generated using unaligned systematic sampling with a 3 × 3 grid.

The major benefit of systematic sampling was that it is the most efficient design for spatially correlated data. In addition, coverage of the entire plot was guaranteed. One disadvantage of systematic sampling was that determining the required sample size was more difficult than the other three methods discussed in this appendix.



**Figure A.1-1. Unaligned Systematic Sampling Design for a  $3 \times 3$  Grid**

#### A.1.2 Kriging Methods and Results

The geostatistical analysis approach was to utilize kriging, a statistical spatial interpolation procedure, to estimate the overall average TCE concentration in soil before and after remediation, and then determine if those concentrations were significantly different.

To meet the objectives of this study, it is sufficient to estimate the overall mean TCE concentration across an entire test plot, rather than estimating TCE concentrations at various spatial locations within a test plot. In geostatistical terms, this is known as global estimation. One approach, and in fact the simplest approach, for calculating a global mean estimate is to calculate the simple arithmetic average (i.e., the equally weighted average) across all available TCE concentrations measured within the plot. However, this approach is appropriate only in cases where no correlation is present in the measured data. Unfortunately, this is a rare situation in the environmental sciences.

A second approach, and the approach taken in this analysis, is to use a spatial statistical procedure called kriging to take account of spatial correlation when calculating the global average. Kriging is a statistical interpolation method for analyzing spatially varying data. It is used to estimate TCE concentrations (or any other important parameter) on a dense grid of spatial locations covering the region of interest, or as a global average across the entire region. At each location, two values are calculated with the kriging procedure: the estimate of TCE concentration (mg/kg), and the standard error of the estimate (also in mg/kg). The standard error can be used to calculate confidence intervals or confidence bounds for the estimates. It should be noted that this calculation of confidence intervals and bounds also requires a serious distributional assumption, such as a normality assumption, which is typically more reasonable for global estimates than for local estimates.

The kriging approach includes two primary analysis steps:

1. Estimate and model spatial correlations in the available monitoring data using a semivariogram analysis.

2. Use the resulting semivariogram model and the available monitoring data to interpolate (i.e., estimate) TCE values at unsampled locations; calculate the statistical standard error associated with each estimated value.

#### A.1.2.1 Spatial Correlation Analysis

The objective of the spatial correlation analysis is to statistically determine the extent to which measurements taken at different locations are similar or different. Generally, the degree to which TCE measurements taken at two locations are different is a function of the distance and direction between the two sampling locations. Also, for the same separation distance between two sampling locations, the spatial correlation may vary as a function of the direction between the sampling locations. For example, values measured at each of two locations, a certain distance apart, are often more similar when the locations are at the same depth, than when they are at the same distance apart but at very different depths.

Spatial correlation is statistically assessed with the semivariogram function, ( $\text{S}(h)$ ), which is defined as follows (Journel and Huijbregts, 1981):

$$2(\text{S}(h)) = E \{ [Z(\underline{x}) - Z(\underline{x} + \underline{h})]^2 \}$$

where  $Z(\underline{x})$  is the TCE measured at location  $\underline{x}$ ,  $\underline{h}$  is the vector of separation between locations  $\underline{x}$  and  $\underline{x} + \underline{h}$ , and  $E$  represents the expected value or average over the region of interest. Note that the location  $\underline{x}$  is typically defined by an easting, northing, and depth coordinate. The vector of separation is typically defined as a three-dimensional shift in space. The semivariogram is a measure of spatial differences, so that small semivariogram values correspond to high spatial correlation, and large semivariogram values correspond to low correlation.

As an initial hypothesis, it is always wise to assume that the strength of spatial correlation is a function of both distance and direction between the sampling locations. When the spatial correlation is found to depend on both separation distance and direction, it is said to be anisotropic. In contrast, when the spatial correlation is the same in all directions, and therefore depends only on separation distance, it is said to be isotropic.

The spatial correlation analysis is conducted in the following steps using the available measured TCE data:

- Experimental semivariogram curves are generated by organizing all pairs of data locations into various separation distance and direction classes (e.g., all pairs separated by 20-25 ft. in the east-west direction  $\vee 22.5^\circ$ ), and then calculating within each class the average squared-difference between the TCE measurements taken at each pair of locations. The results of these calculations are plotted against separation distance and by separation direction.
- To help fully understand the spatial correlation structure, a variety of experimental semivariogram curves may be generated by subsetting the data into discrete zones, such as different depth horizons. If significant differences are found in the semivariograms they are modeled separately; if not, the data are pooled together into a single semivariogram.
- After the data have been pooled or subsetted accordingly, and the associated experimental semivariograms have been calculated and plotted, a positive-definite

analytical model is fitted to each experimental curve. The fitted semivariogram model is then used to input the spatial correlation structure into the subsequent kriging interpolation step.

#### A.1.2.2 Interpolation Using Ordinary Kriging

Ordinary kriging is a linear geostatistical estimation method which uses the semivariogram function to determine the optimal weighting of the measured TCE values to be used for the required estimates, and to calculate the estimation standard error associated with the estimates (Journel and Huijbregts, 1981). In a sense, kriging is no different from other classical interpolation and contouring algorithms. However, kriging is different in that it produces statistically optimal estimates and associated precision measures. It should be noted that the ordinary kriging variance, while easy to calculate and readily available from most standard geostatistical software packages, may have limited usefulness in cases where local estimates are to be calculated, and the data probability distribution is highly skewed or non-gaussian. The ordinary kriging variance is more appropriately used for global estimates and symmetric or gaussian data distributions. The ordinary kriging variance provides a standard error measure associated with the data density and spatial data arrangement relative to the point or block being kriged. However, the ordinary kriging variance is independent of the data values themselves, and therefore may not provide an accurate measure of local estimation precision.

#### A.1.2.3 TCE Data Summary

Semivariogram and kriging analyses were conducted on data collected from two test plots; one plot used Six-Phase Heating<sup>TM</sup> (SPH) technology, and the other used a standard oxidation method to remove TCE. Each plot was approximately 50 by 75 feet in size, and was sampled via 25 drill holes, half before and half after remediation. The location of each drill hole was recorded by measuring the distance in the northing and easting directions from a designated point on the Cape Canaveral Air Station. The documented coordinates for each drill hole on the SPH and OX plots are depicted within Figure A.1-2. The same locations are also shown in Figure A.1-3 after we rotated both plots by 30 degrees and shifted the coordinates in order to produce a posting map that was compatible with the kriging computer software.

Each point within Figures A.1-2 and A.1-3 represents a single drill hole. Recall that pre- and post-remediation TCE measurements were collected in order to analyze the effectiveness of the contaminant removal methods. Thus, the drill holes were strategically placed so that pre and post information could be gathered within a reasonable distance of one another (i.e., the holes were approximately paired). In addition, for both the SPH and the OX plots, an extra or twinned post-remediation hole was drilled (see pre/post pair # 10B and 17B on Figures A.1-2 and A.1-3). Since our approach for the kriging analysis considered the pre- and post-remediation data as independent data sets (see Section 1.0), we included the duplicate holes in our analyses, even though a corresponding pre-remediation hole did not exist.

The cores were drilled at least 44 feet deep; and the largest drill hole extends 48 feet. With few exceptions, TCE measurements were collected every two feet. Thus, approximately 20 to 25 two-foot core sections were analyzed from each drill hole. The vertical location of each core section was identified by the elevation of the midpoint of the section above sea level. At the time of data collection, the surface elevation at the location of the drill hole, as well as the top and bottom depths of each core section (rounded to the nearest half of a foot), were recorded. Hence, the elevation of each sample was calculated by the subtracting the average of the top and bottom depths from the surface elevation. For example, if a sample was collected from a core section

that started and ended at 20 and 22 feet below a ground surface elevation of 5.2 feet, then the sample elevation equaled  $5.2 - (20+22)/2 = 15.8$  feet above sea level.

In some cases, field duplicate samples were collected by splitting an individual two-foot core section. In order to optimize the additional data, we used all measurements when evaluating spatial correlation with the semivariogram analysis, and when conducting the kriging analysis. However, to remain compatible with the kriging software, it was necessary to shift the location of the duplicate data slightly, by adding one-tenth of a foot to the easting coordinate. Table A.1-1 summarizes the number of two-foot sections from which more than one sample was collected.

**Table A.1-1. Number of Field Duplicate Measurements Taken from the SPH and OX Plots**

Plot	Pre/Post	Number of Two-Foot Sections From Which		Total
		1 Sample was Drawn	> 1 Sample was Drawn	
SPH	Pre	242	20	262
	Post	246	28	292
OX	Pre	251	16	267
	Post	276	12	288

There were also cases where the observed TCE concentration for a particular sample occurred below the analytical method detection limit (MDL). In such cases, the measurement that was included in our analyses equaled one-half of the given MDL. Table A.1-2 summarizes the number of observations that were below the MDL.

**Table A.1-2. Number of Measurements (including Duplicates) Below the Minimum Detection Limit**

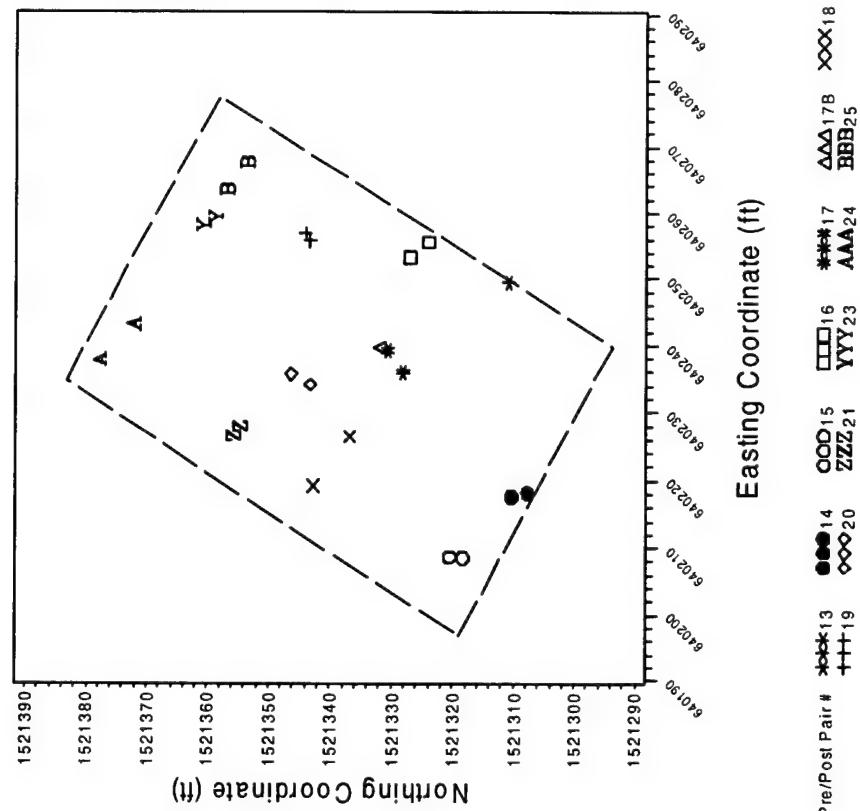
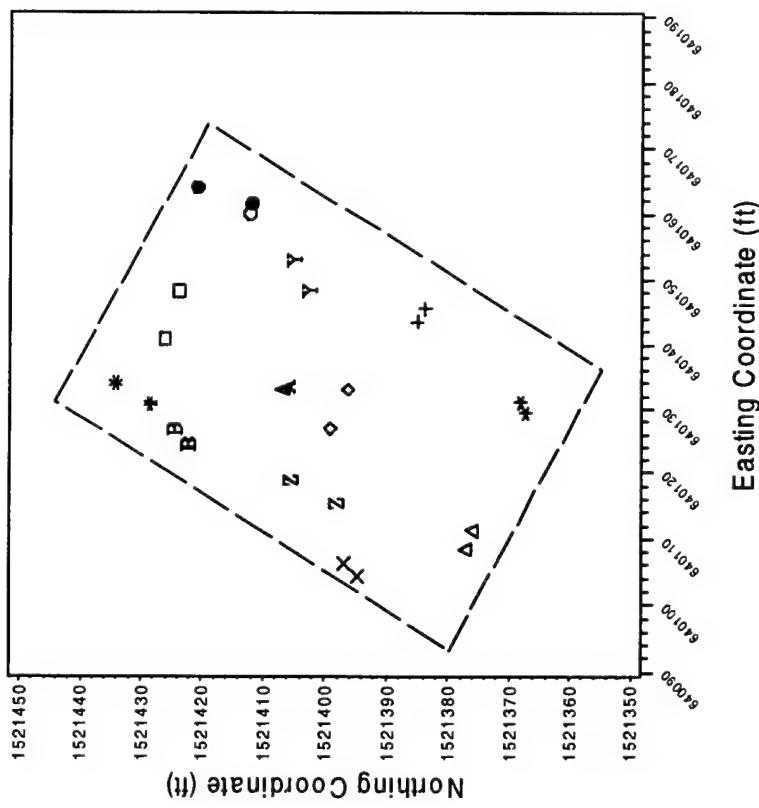
Plot	Pre/Post	Number of Samples		Total
		Below MDL	Above MDL	
SPH	Pre	47	231	278
	Post	29	276	305
OX	Pre	20	266	286
	Post	156	144	300

When a two-foot section was removed from the core, the sample was identified by the easting, northing, and elevation coordinates. In addition, the geologic stratum, or soil type of the sample, was also documented. These strata and soil types included the vadose zone, upper sand unit (USU), middle fine-grained unit (MFGU), and lower sand unit (LSU). Note that the stratum of the sample was not solely determined by depth, but also by inspection by a geologist.

All of the data used in the geostatistical analyses are listed in Appendix A (with all field duplicates). Tables A.1-3 and A.1-4 provide summary statistics by layer and depth for pre- and post-remediation measurements. The minimum and maximum values provide the overall range of the data; the mean or average TCE measurement estimates (via simple arithmetic averaging) the amount of TCE found within the given layer and depth; and the standard deviation provides a sense of the overall spread of the data. Note that our analyses focus on the three deepest layers, USU, MFGU and LSU.

## SPH

## Oxidation

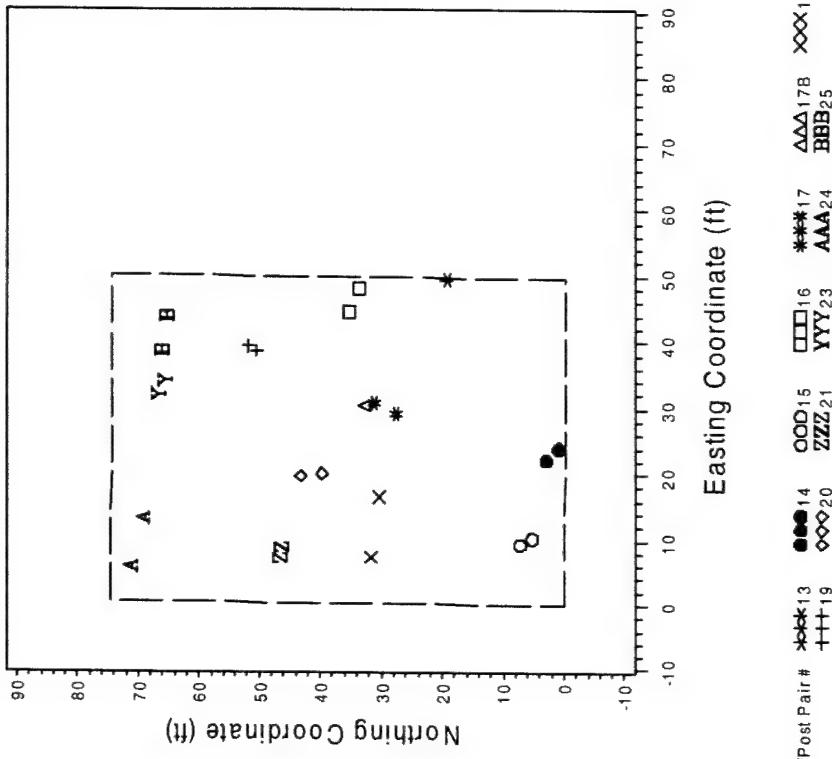
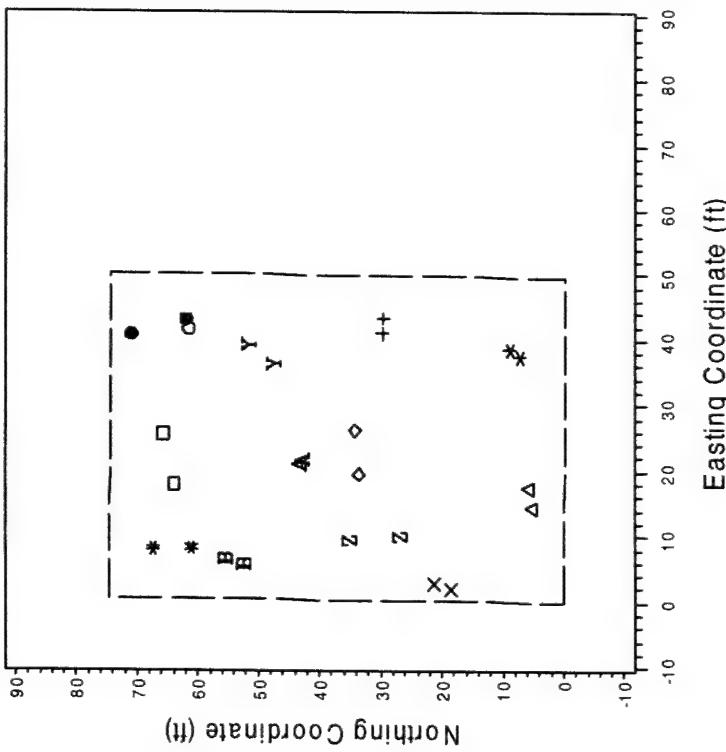


**Figure A.1-2. Original Posting Maps of SPH and Oxidation Plots**

(Note that pre/post pair # 13 has two drill holes that are extremely close to one another)

# SPH

# Oxidation



**Figure A.1-3. Rotated Posting Maps of SPH and Oxidation Plots**

(Note that pre/post pair # 13 has two drill holes that are extremely close to one another.)

**Table A.1-3.** Summary Statistics for Data Collected From SPH Plot by Layer and Depth

Feet Above Sea Level (MSL)		Pre-Treatment			Post-Treatment					
Layer	N	Minimum (mg/kg)	Maximum (mg/kg)	Mean (mg/kg)	Std. Dev. (mg/kg)	N	Minimum (mg/kg)	Maximum (mg/kg)	Mean (mg/kg)	Std. Dev. (mg/kg)
VADOSE	10 to 12	1	7.78	7.78		2	0.26	0.77	0.51	0.36
	8 to 10	1	5.29	5.29		6	0.25	6.00	2.67	2.62
	6 to 8	6	0.14	9.24	2.01	3.59	12	0.25	6.00	1.84
	4 to 6	12	0.14	4.63	1.25	1.63	13	0.21	12.00	2.61
	2 to 4	12	0.10	10.52	1.75	3.16	13	3.00	40.22	9.32
	0 to 2	10	0.17	48.74	5.26	15.29	3	10.00	72.00	47.67
	-2 to 0	2	0.20	1.10	0.65	0.64				
	Total	44	0.10	48.74	2.61	7.55	49	0.21	72.00	6.88
	0 to 2	2	0.71	8.84	4.77	5.75	10	5.00	90.00	30.31
	-2 to 0	9	0.18	12.46	2.27	4.06	12	0.22	114.00	20.85
USU	-4 to -2	11	0.18	6.46	1.65	2.09	9	0.22	71.00	18.84
	-6 to -4	10	0.18	4.01	1.05	1.24	12	0.16	126.00	36.26
	-8 to -6	13	0.17	121.67	10.73	33.41	12	0.26	197.00	50.52
	-10 to -8	13	0.20	341.80	51.64	122.88	13	1.00	4295.43	358.08
	-12 to -10	11	0.19	1935.01	182.22	581.52	11	0.17	1248.08	154.42
	-14 to -12	12	0.20	107.82	22.01	32.52	11	5.00	135.00	62.56
	-16 to -14	10	9.20	1835.15	224.50	569.37	10	4.00	213.00	96.89
	-18 to -16	5	10.77	259.76	86.43	101.53	2	6.00	64.00	35.00
	-20 to -18	2	26.27	112.13	69.20	60.71	1	20.00	20.00	20.00
	Total	98	0.17	1935.01	60.75	271.45	103	0.16	4295.43	95.78
MFCU	-14 to -12	1	820.43	820.43		1	3927.05	3927.05	3927.05	437.80
	-16 to -14	2	292.17	526.14	409.16	165.45	5	12.00	401.30	252.87
	-18 to -16	5	183.22	905.90	2192.46	3844.52	12	4.00	5560.77	704.64
	-20 to -18	13	26.37	1960.91	3314.22	6670.74	12	13.00	403.00	215.36
	-22 to -20	10	54.64	541.79	196.80	148.15	8	10.00	319.00	131.66
	-24 to -22	8	17.00	11085.00	1533.59	3871.12	4	7.00	140.00	55.25
	-26 to -24	3	2.24	5345.08	1783.27	3084.62	2	3.00	19.00	11.00
	-28 to -26	2	0.39	0.39	0.00	2	5.00	23.00	14.00	12.73
	-30 to -28	2	0.20	1.40	0.80	0.85	2	1.00	1.00	0.00
	-32 to -30	1	0.68	0.68	0.68	1	3.00	3.00	3.00	0.00
LSU	Total	47	0.20	19609.91	1601.61	4152.73	49	1.00	5560.77	358.38
	-2 to -18					1	1217.00	1217.00	1217.00	
	-2 to -20	3	34.76	349.12	186.05	157.51	5	34.00	464.64	233.38
	-24 to -22	6	4.79	623.63	176.84	231.51	10	20.70	287.00	139.97
	-26 to -24	9	0.18	1024.58	213.91	332.94	11	35.00	429.15	192.80
	-28 to -26	11	0.28	23361.76	4599.56	8705.84	12	63.00	473.85	279.32
	-30 to -28	10	0.23	8061.67	1430.78	2922.44	12	2.00	264.00	143.55
	-32 to -30	9	0.21	28167.63	3338.38	9314.75	11	9.00	335.08	123.18
	-34 to -32	12	0.43	33099.93	3357.69	9549.49	12	0.17	511.00	167.27
	-36 to -34	12	5.75	41043.56	7635.34	15205.72	12	0.19	364.00	144.99
Total	-38 to -36	12	11.76	37104.00	6980.34	12891.67	3	2.00	59.00	23.00
	-40 to -38	1	1.46	1.46	1.46	1.46				
Total	85	0.18	41043.56	3696.17	9459.97	89	0.17	1217.00	1217.00	176.47

**Table A.1-4.** Summary Statistics for Data Collected From OX Plot by Layer and Depth

#### A.1.2.4 Semivariogram Results

In this study, the computer software used to perform the geostatistical calculations was Battelle's BATGAM software, which is based on the GSLIB Software written by the Department of Applied Earth Sciences at Stanford University, and documented and released by Prof. Andre Journel and Dr. Clayton Deutsch (Deutsch and Journel, 1998). The primary subroutine used to calculate experimental semivariograms was GAMV3, which is used for three-dimensional irregularly spaced data.

For the three-dimensional spatial analyses, horizontal separation distance classes were defined in increments of 5 ft. with a tolerance of 2.5 ft., while vertical distances were defined in increments of 2 ft. with a tolerance of 1 ft. Horizontal separation directions were defined, after rotation 30° west from North (see Figures A.1-2 and A.1-3), in the four primary directions of north, northeast, east, and southeast with a tolerance of 22.5°.

Data were analyzed separately for the SPH and OX plots, and vertically the data were considered separately by layer (i.e., USU, MFGU and LSU layers). Semivariogram and kriging analyses were not performed with the vadose data since the pre-remediation TCE concentrations were already relatively low and insignificant. Results from the semivariogram analyses are presented in Figures A.1-4 to A.1-15, as well as Table A.1-5. The key points indicated in the semivariogram analysis results are as follows:

- (a) For all experimental semivariograms calculated with the TCE data, no horizontal directional differences (i.e., anisotropies) were observed; however, strong anisotropy for the horizontal versus vertical directions was often observed. Therefore, in Figures 3 through 14 the omnidirectional horizontal semivariogram (experimental and model) is shown along with the vertical semivariogram (experimental and model).
- (b) In all cases, the experimental semivariograms are relatively variable due to high data variability and modest sample sizes. As a result, the semivariogram model fitting is relatively uncertain, meaning that a relatively wide range of semivariogram models could adequately fit the experimental semivariogram points. This probably does not affect the TCE estimates (especially the global estimates), but could significantly affect the associated confidence bounds.
- (c) The models shown in Figures 3 through 14 are all gaussian semivariogram models, chosen to be consistent with the experimental semivariogram shapes found for all twelve TCE data sets at this Cape Canaveral site. The fitted semivariograms model parameters are listed in Table 5.

**Table A.1-5. Fitted Semivariogram Model Parameters for TCE at Cape Canaveral**

Figure No.	Data Set			Semivariogram				
	Plot	Layer	Pre- or Post-Remediation	Gaussian Type	Nugget Var. ( $\text{mg/kg}^2$ )	Total Sill Var. ( $\text{mg/kg}^2$ )	Omni-Horizontal Range (ft.)	Vertical Range (ft.)
3	SPH	USU	PRE	Anisotropic	$6.0 \times 10^3$	$6.4 \times 10^4$	23	3
4	SPH	USU	POST	Anisotropic	$2.0 \times 10^4$	$1.9 \times 10^5$	35	3
5	SPH	MFGU	PRE	Anisotropic	$1.0 \times 10^6$	$2.0 \times 10^7$	35	5
6	SPH	MFGU	POST	Anisotropic	$5.0 \times 10^4$	$6.0 \times 10^5$	35	5
7	SPH	LSU	PRE	Isotropic	$2.5 \times 10^7$	$8.5 \times 10^7$	9	9
8	SPH	LSU	POST	Anisotropic	$4.0 \times 10^3$	$2.0 \times 10^4$	23	3
9	OX	USU	PRE	Anisotropic	$5.0 \times 10^4$	$3.0 \times 10^5$	12	3
10	OX	USU	POST	Isotropic	$5.0 \times 10^1$	$4.0 \times 10^2$	3	3
11	OX	MFGU	PRE	Anisotropic	$2.5 \times 10^6$	$2.0 \times 10^7$	35	3
12	OX	MFGU	POST	Anisotropic	$2.0 \times 10^5$	$1.4 \times 10^6$	52	3
13	OX	LSU	PRE	Anisotropic	$1.0 \times 10^6$	$1.0 \times 10^7$	23	3
14	OX	LSU	POST	Anisotropic	$7.0 \times 10^4$	$6.7 \times 10^5$	35	3

### A.1.2.5 Kriging Results

The kriging analysis was performed using the BATGAM software and GSLIB subroutine KT3D. To conduct this analysis, each plot was defined as a set of vertical layers and sub-layers.

Estimated mean TCE concentrations were then calculated via kriging for each sub-layer separately, as well as across the sub-layers. The vertical layering for kriging was consistent with the semivariogram modeling:

- (a) Kriging the SPH plot was performed separately for the USU, MFGU and LSU layers. The USU layer was sub-divided into 11 two-foot sub-layers extending across elevations from -20 to +2 ft. The MFGU layer was sub-divided into 10 two-foot sub-layers extending across elevations from -32 to -12 ft. The LSU layer was sub-divided into 11 two-foot sub-layers from elevations of -40 to -18 ft.
- (b) Kriging of the OX plot was also done separately for the USU, MFGU and LSU layers. The USU layer consisted of 11 two-foot sub-layers across elevations from -18 to +4 ft. The MFGU layer consisted of 9 sub-layers across elevations from -30 to -12 ft. The LSU layer consisted of 9 sub-layers across elevations from -38 to -20 ft.
- (c) For kriging of the two-foot sub-layers, the data search was restricted to consider only three sub-layers, the current sub-layer and that immediately above and below. The data search was not restricted horizontally.

(d) For kriging of an entire layer (i.e., USU or MFGU or LSU separately), the data search considered all available data at all elevations. Note that by extending the data search radius to include all data within a plot, an implicit assumption is made that the semivariogram model holds true for distances up to about 100 ft., which are distances beyond those observable with this dataset in the experimental semivariograms. This assumption seems reasonable given the relatively short dimensions of the SPH and OX plots.

Results from the kriging analysis are presented in Tables A.1-6 and A.1-7 for the SPH and OX pre- and post-remediation data, and for each of USU, MFGU and LSU layers, as well as by sub-layer within each layer. Because of the shortcomings of using the ordinary kriging variance (discussed in Section 1.0) for local estimates, confidence bounds are only presented in Tables 6 and 7 for the global layer estimates (shaded rows). In cases where the upper confidence bound for the post-remediation average TCE concentration falls below the lower confidence bound for the pre-remediation average TCE concentration, the post-remediation TCE concentrations are statistically significantly lower than the pre-remediation TCE concentrations (denoted with a \* in the tables). The estimated TCE reductions, expressed on a percentage basis, are also shown in Tables A.1-6 and A.1-7 and generally (with the exception of the TCE increase in the SPH USU layer) vary between 70% and 96%, based on the global estimates.

Table A.1-8 shows how the TCE concentration estimates (average, lower bound, and upper bound as determined in Table A.1-7) for Oxidation Plot are weighted and converted into TCE masses. The concentration estimates in the three stratigraphic units are multiplied by the number of grid cells sampled (N) in each stratigraphic unit and the mass of dry soil in each cell (26,831.25 kg). The mass of soil in each grid cell is the volume of each 18.75 ft x 16.67 ft x 2 ft grid cell (the area of the plot divided into a 4 x 3 grid; the thickness of each grid cell is 2 ft).

**Table A.1-6. Kriging Results for TCE in the SPH Plot**

Layer	Feet Above Sea Level (MSL)	Pre-Remediation TCE (mg/kg)	Post-Remediation TCE (mg/kg) / Percent Reduction
USU	0 to 2	3	32
	-2 to 0	2	21
	-4 to -2	2	18
	-6 to -4	1	32
	-8 to -6	14	46
	-10 to -8	31	297
	-12 to -10	124	325
	-14 to -12	118	122
	-16 to -14	182	78
	-18 to -16	245	61
	-20 to -18	88	41
	Total	64	112 / -75%
	95% C.I.	(19, 110)	(38, 186)
	90% C.I.	(26, 103)	(49, 174)
	80% C.I.	(34, 94)	(63, 160)
	-14 to -12	.	1450
	-16 to -14	412	606
MFGU	-18 to -16	1375	635
	-20 to -18	2125	478
	-22 to -20	1765	181
	-24 to -22	1419	119
	-26 to -24	2809	54
	-28 to -26	1705	12
	-30 to -28	1	3
	-32 to -30	1	.
	Total	1655	408 / 75%
	95% C.I.	(251, 3059)	(165, 650)
	90% C.I.	(473, 2837)	(204, 612)
	80% C.I.	(731, 2579)	(248, 567)*
LSU	-20 to -18	.	512
	-22 to -20	140	204
	-24 to -22	151	166
	-26 to -24	207	180
	-28 to -26	2394	239
	-30 to -28	2462	189
	-32 to -30	2246	135
	-34 to -32	3190	153
	-36 to -34	7241	154
	-38 to -36	8225	118
	-40 to -38	5615	.
	Total	4092	183 / 96%
	95% C.I.	(1463, 6721)	(154, 212)*
	90% C.I.	(1879, 6305)	(159, 208)*
	80% C.I.	(2362, 5822)	(164, 202)*

\* TCE reduction is statistically significant.

**Table A.1-7. Kriging Results for TCE in the OX Plot**

Layer	Feet Above Sea Level (MSL)	Pre-Remediation TCE (mg/kg)	Post-Remediation TCE (mg/kg) / Percent Reduction
USU	2 to 4	2	1
	0 to 2	1	5
	-2 to 0	1	6
	-4 to -2	2	7
	-6 to -4	3	9
	-8 to -6	9	5
	-10 to -8	31	12
	-12 to -10	53	16
	-14 to -12	613	6
	-16 to -14	760	4
	-18 to -16	167	.
	Total	146	8 / 95%
	95% C.I.	(45, 246)	(4, 11)*
	90% C.I.	(61, 230)	(4, 11)*
	80% C.I.	(80, 212)	(5, 10)*
MFGU	-14 to -12	7963	3593
	-16 to -14	9414	1501
	-18 to -16	2684	135
	-20 to -18	1508	619
	-22 to -20	2655	196
	-24 to -22	220	30
	-26 to -24	150	8
	-28 to -26	97	.
	-30 to -28	71	.
	Total	1922	570 / 70%
	95% C.I.	(712, 3133)	(230, 909)
	90% C.I.	(903, 2942)	(284, 856)*
	80% C.I.	(1126, 2719)	(346, 793)*
LSU	-22 to -20	4665	2021
	-24 to -22	10048	954
	-26 to -24	4796	846
	-28 to -26	2036	823
	-30 to -28	1876	245
	-32 to -30	1780	102
	-34 to -32	1453	73
	-36 to -34	1972	183
	-38 to -36	2491	.
	Total	2282	486 / 79%
	95% C.I.	(1578, 2986)	(311, 660)*
	90% C.I.	(1690, 2875)	(339, 632)*
	80% C.I.	(1819, 2746)	(371, 600)*

\* TCE reduction is statistically significant.

**Table A.1-8. Calculating Total TCE Masses based on TCE Average Concentrations and Upper and Lower Bounds**

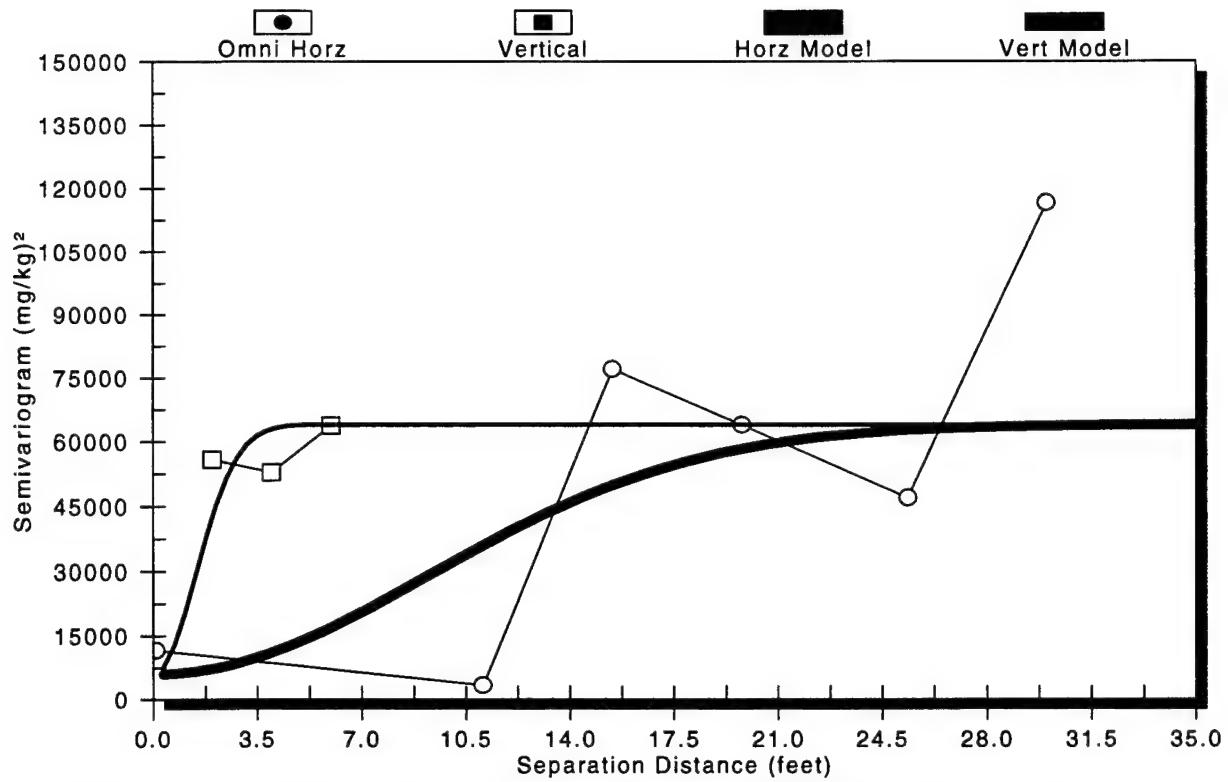


Figure A.1-4. Pre-Remediation TCE Semivariograms for SPH Plot and USU Layer

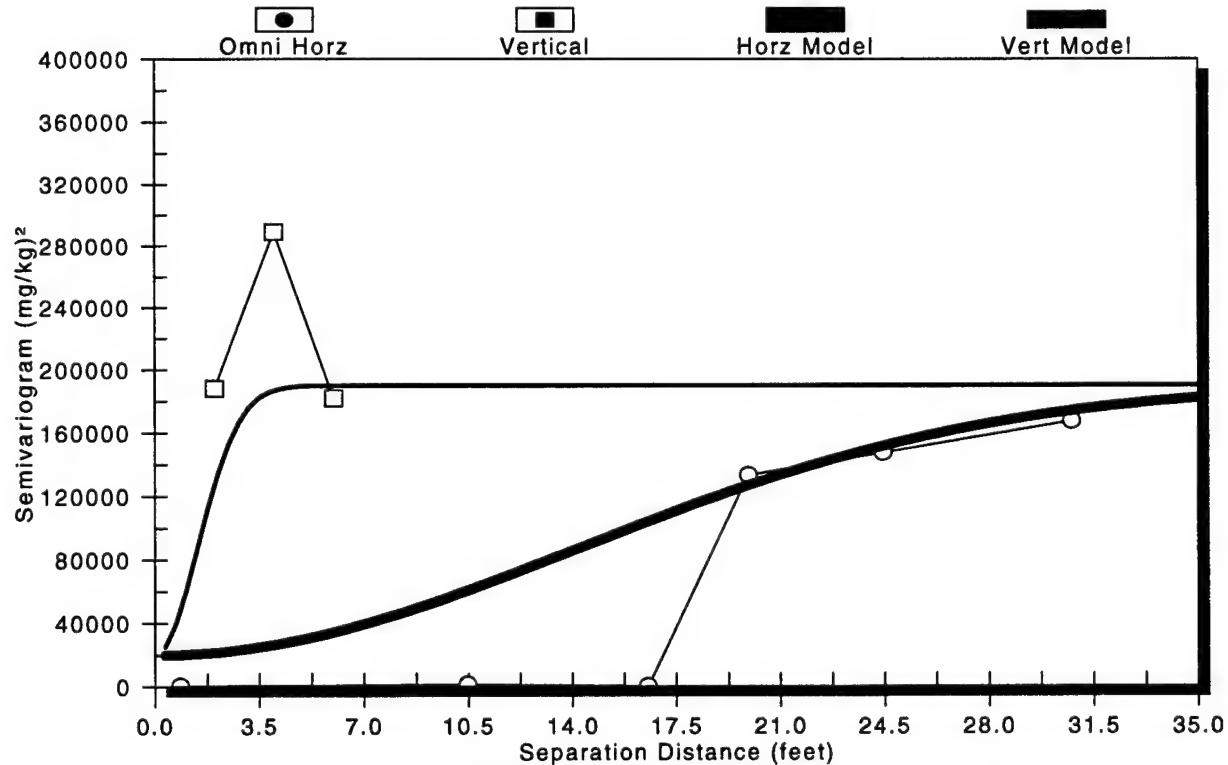
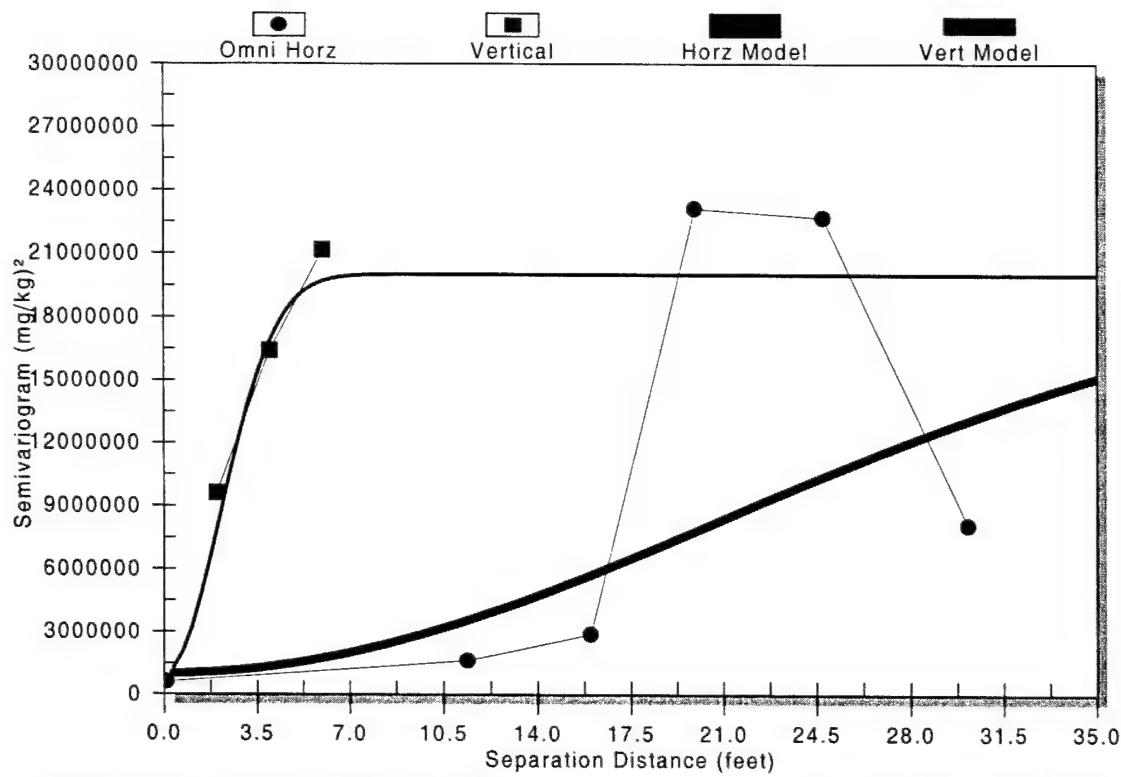
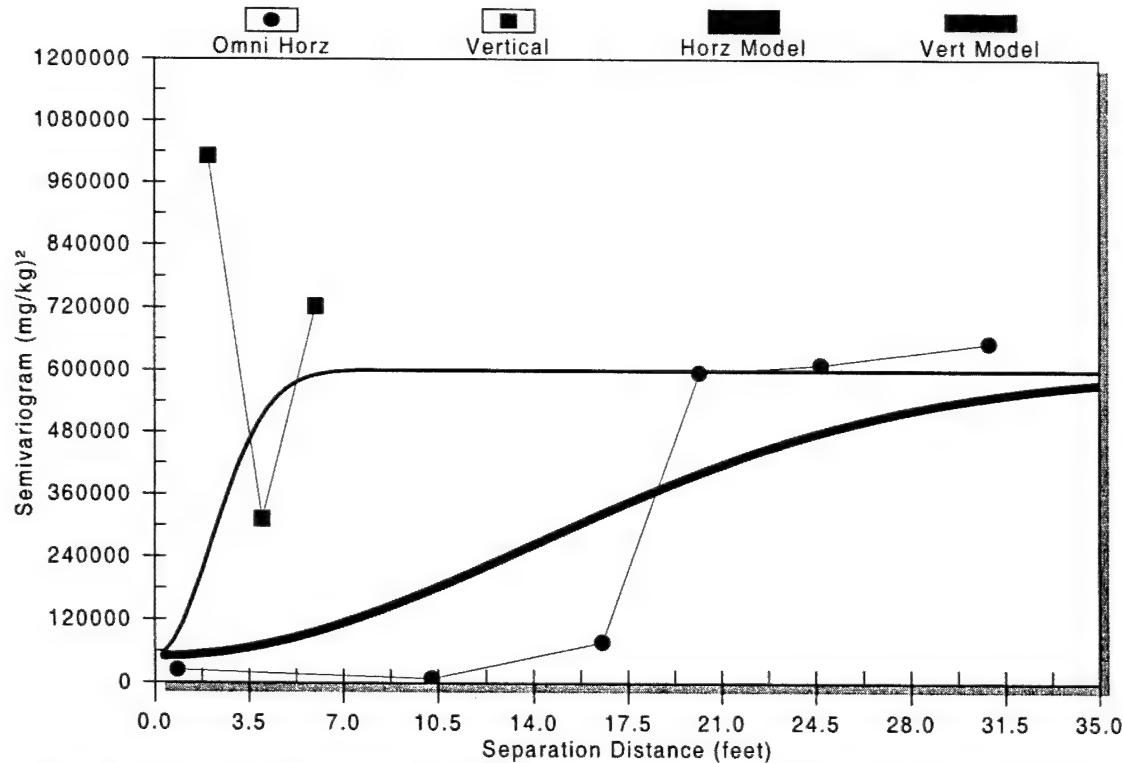


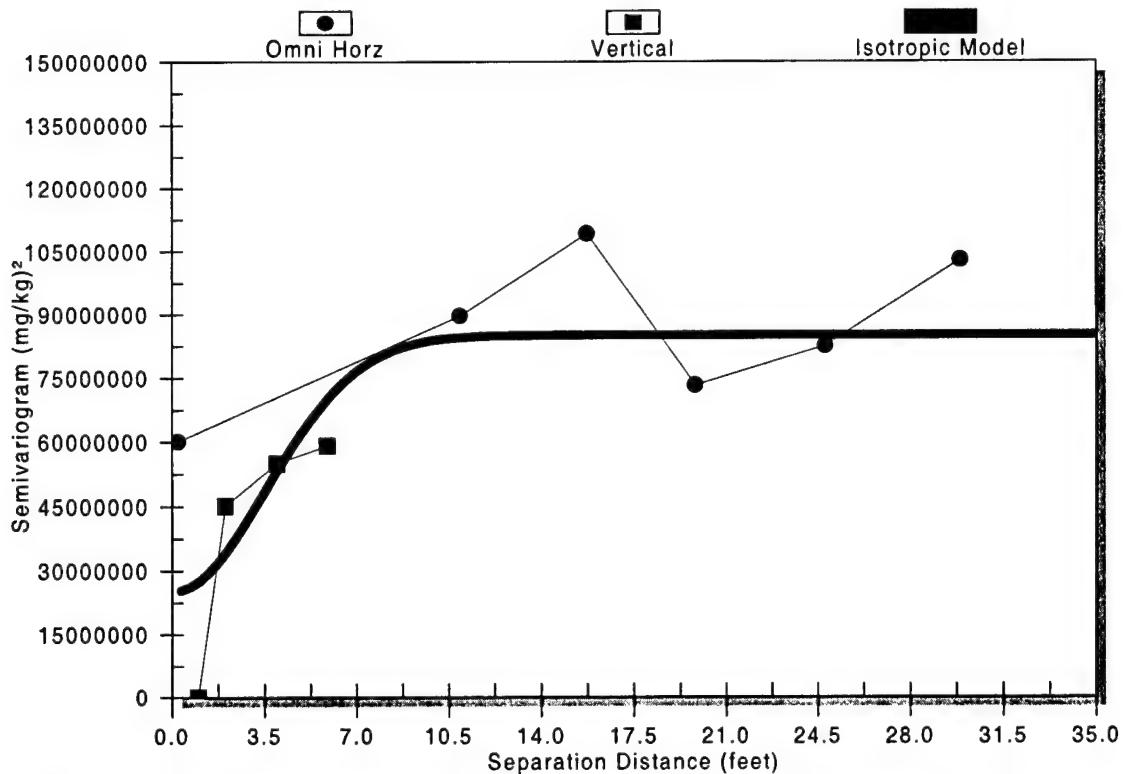
Figure A.1-5. Post-Remediation TCE Semivariograms for SPH Plot and USU Layer



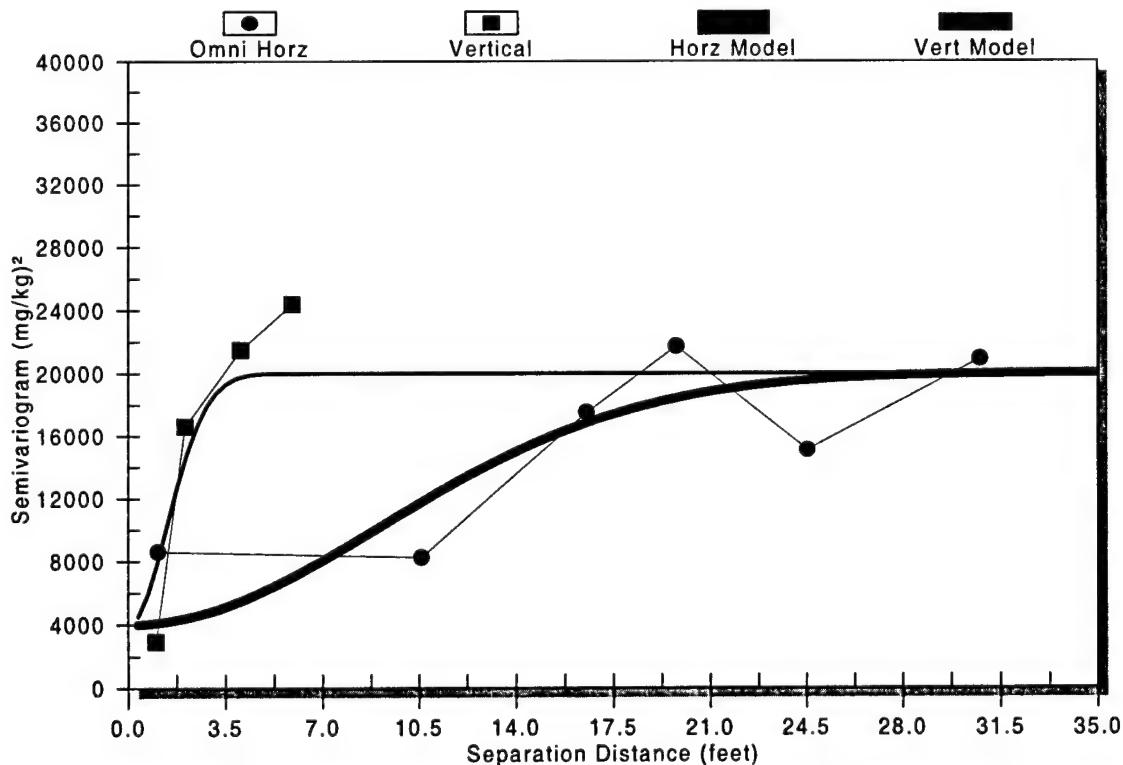
**Figure A.1-6. Pre-Remediation TCE Semivariograms for SPH Plot and MFGU Layer**



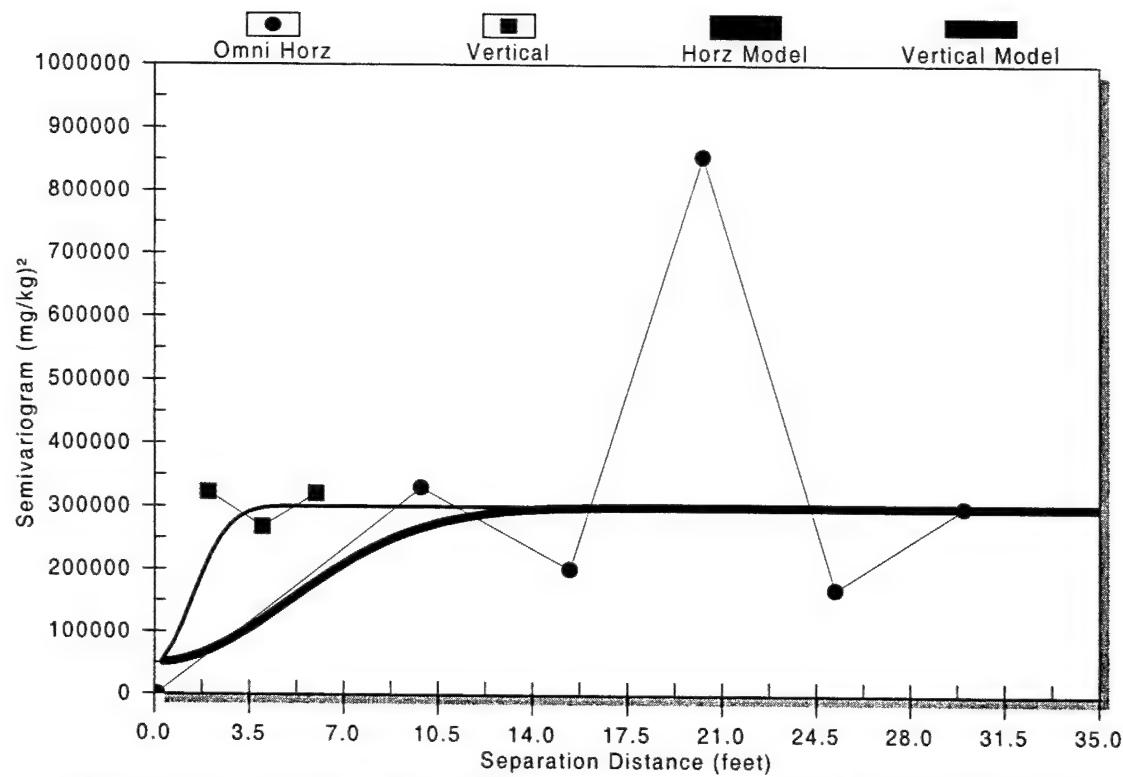
**Figure A.1-7. Post-Remediation TCE Semivariograms for SPH Plot and MFGU Layer**



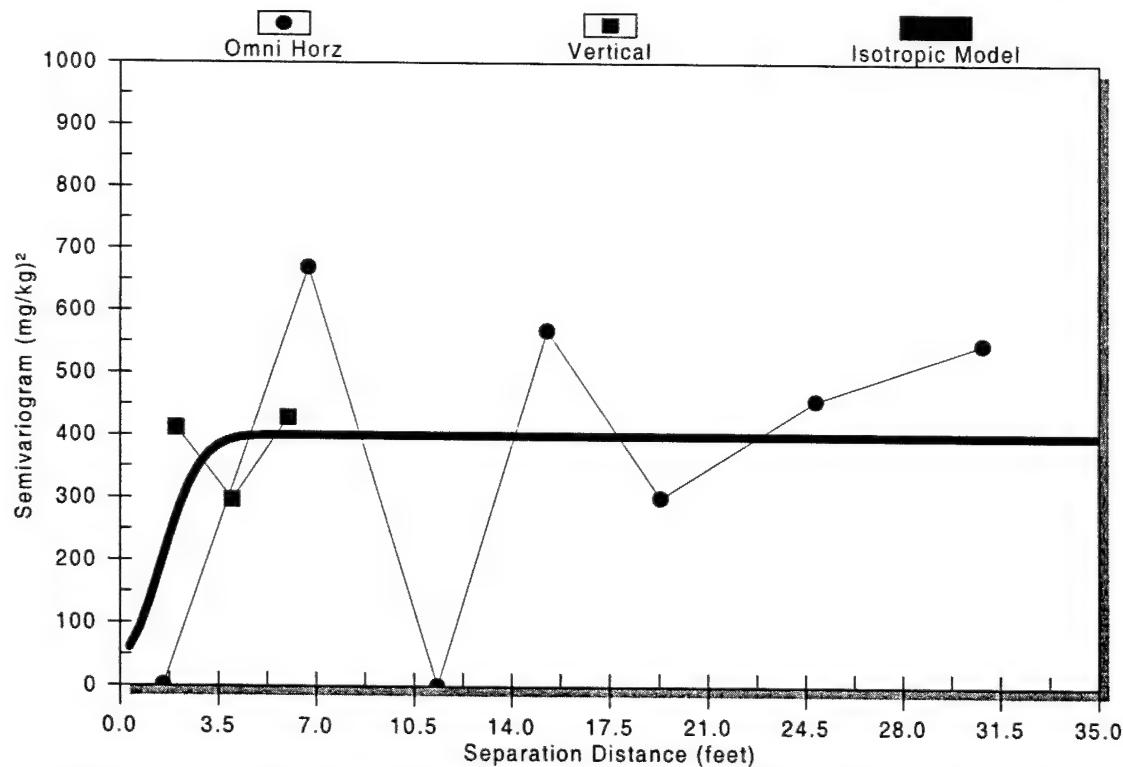
**Figure A.1-8. Pre-Remediation TCE Semivariograms for SPH Plot and LSU Layer**



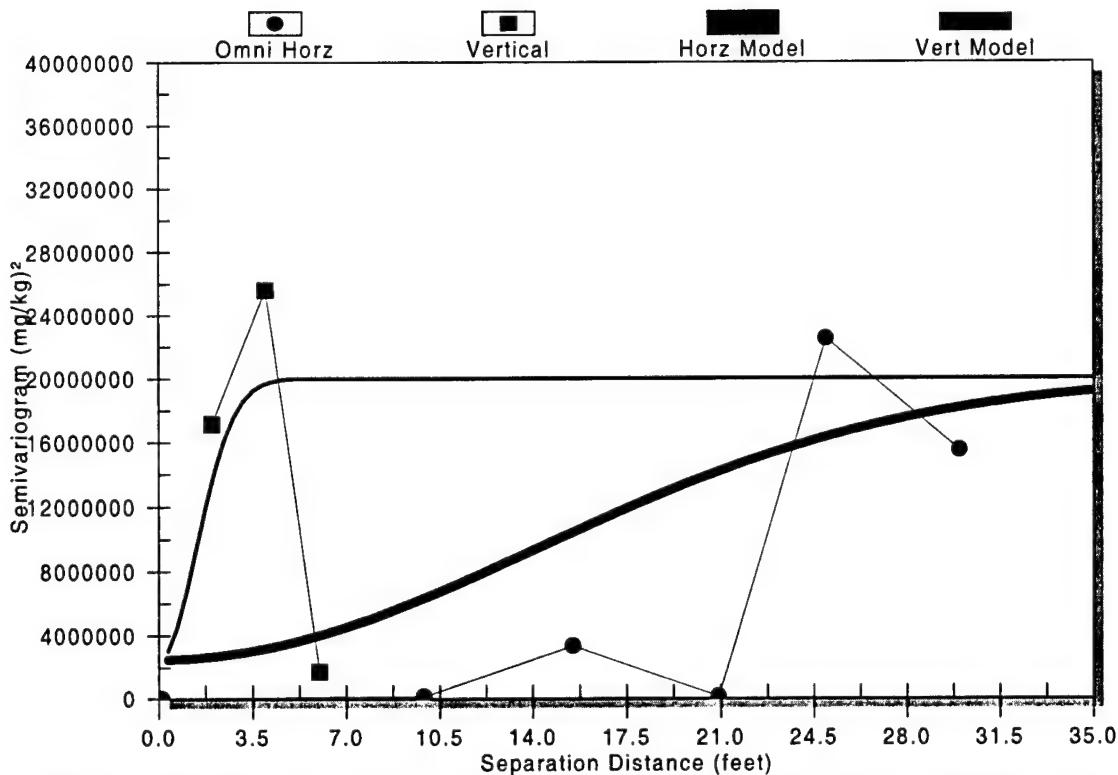
**Figure A.1-9. Post-Remediation TCE Semivariograms for SPH Plot and LSU Layer**



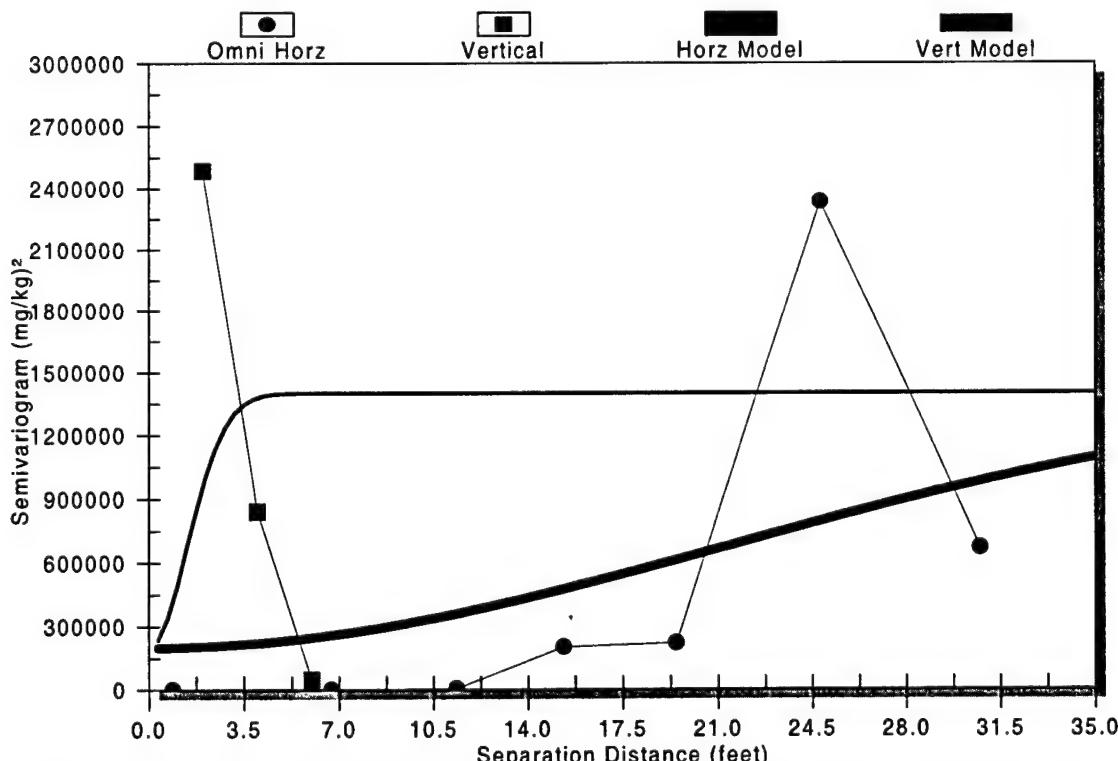
**Figure A.1-10. Pre-Remediation TCE Semivariograms for OX Plot and USU Layer**



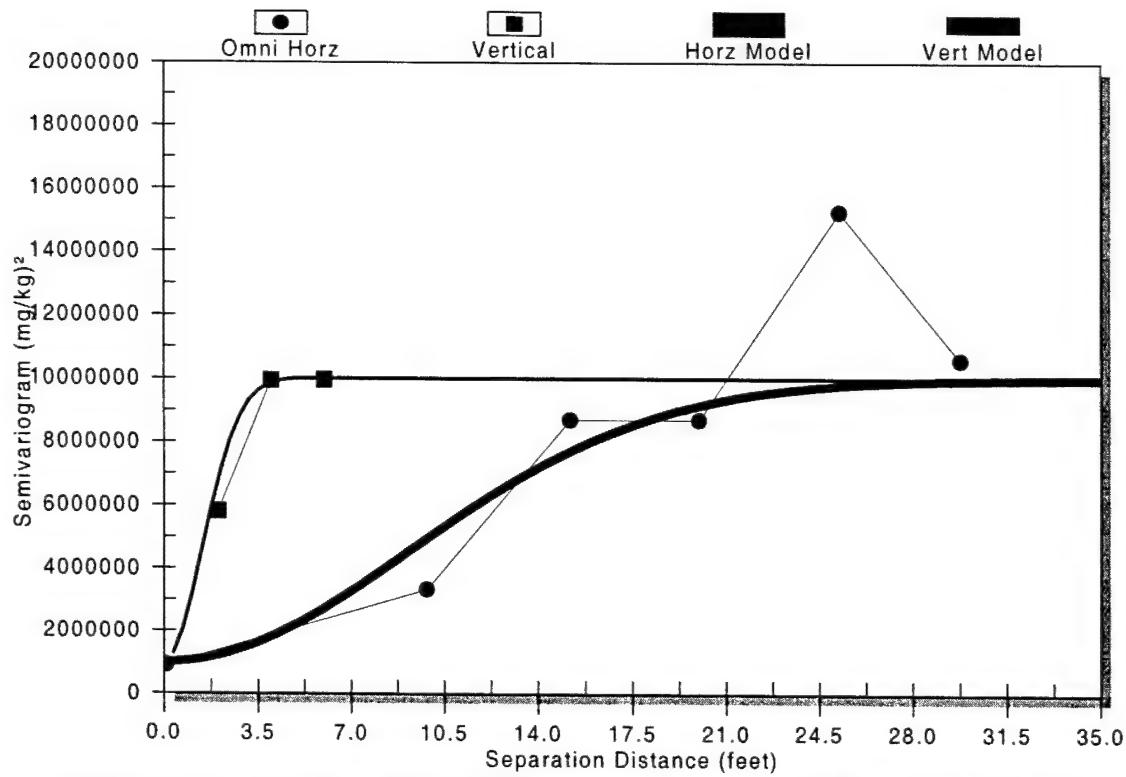
**Figure A.1-11. Post-Remediation TCE Semivariograms for OX Plot and USU Layer**



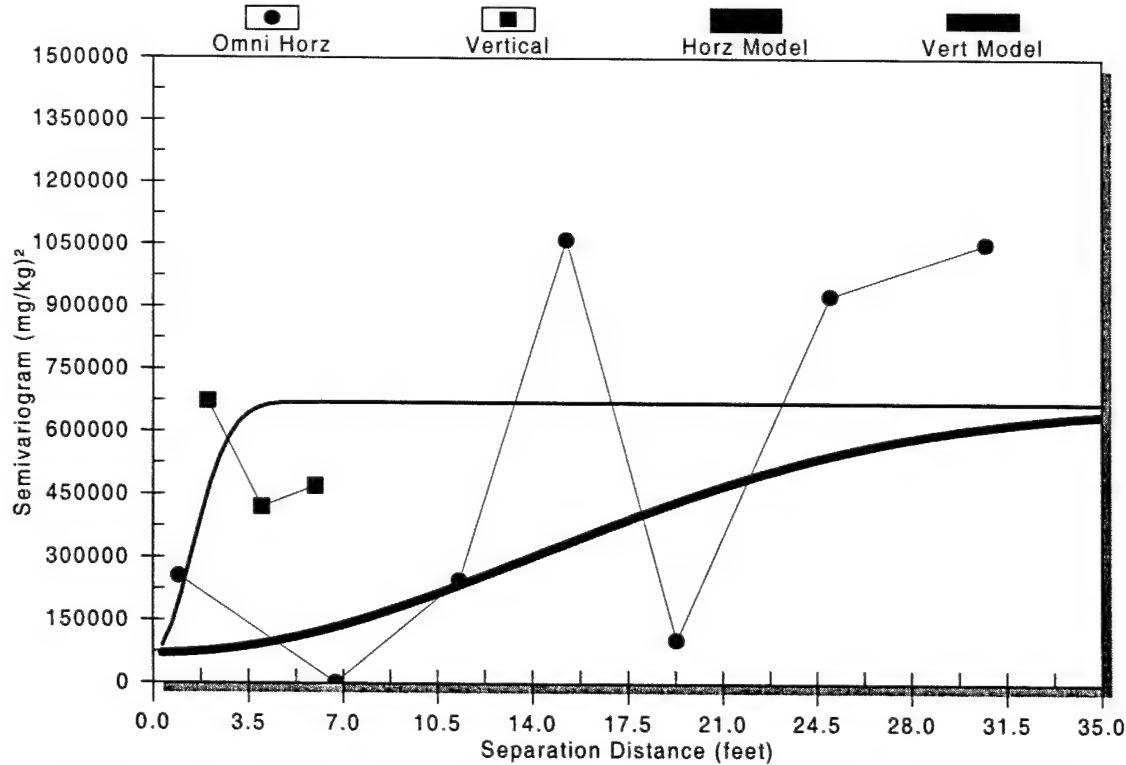
**Figure A.1-12. Pre-Remediation TCE Semivariograms for OX Plot and MFGU Layer**



**Figure A.1-13. Post-Remediation TCE Semivariograms for OX Plot and MFGU Layer**



**Figure A.1-14. Pre-Remediation TCE Semivariograms for OX Plot and LSU Layer**



**Figure A.1-15. Post-Remediation TCE Semivariograms for OX Plot and LSU Layer**

### A.1.3 Pairwise Comparison Methods and Results

The primary objectives of the IDC DNAPL Removal/Destruction Demonstration Project that affected the data collection effort during each technology demonstration was to determine the extent to which DNAPL levels decrease across the entire test plot due to the application of the technology. The statistical design for data collection and analysis presented in the project QAPP was based on testing the hypothesis that a DNAPL removal/destruction technology could reduce the levels of DNAPL by at least 90% over the period of treatment. This objective applies to the entire vertical extent of the test plot as well as to subsets of the test plot defined by geologic strata.

The experimental design called for the collection of one pre-and post-treatment soil core sample from each of 12 grid cells. Sampling locations were chosen using an unaligned systematic sampling plan, with post-treatment sampling locations selected to be in proximity to the pre-treatment sampling locations. Each sample was to be divided into two-foot sections for which DNAPL levels were to be determined. Data analysis was based on the two-foot core sections as the experimental units.

#### A.1.3.1 Pairwise Comparison Method

The statistical hypotheses corresponding to the goal of a 90% reduction in DNAPL levels can be written as

$$H_0: \frac{\mu_1}{\mu_0} \geq 0.1 \text{ vs } H_A: \frac{\mu_1}{\mu_0} < 0.1,$$

where  $\mu_0$  is the initial mean DNAPL concentration and  $\mu_1$  is the mean DNAPL concentration after treatment. Because DNAPL levels were expected to have a log-normal probability distribution and the form of the hypothesis test is a comparison of the ratio of means (versus the difference in means), the QAPP proposed testing the hypotheses using a Student's t-test applied to the logarithms of the observed DNAPL concentrations. However, initial examination of the data from both oxidation and SPH treatment plots showed that the ratio of post-treatment to pre-treatment DNAPL concentrations were modeled well by a normal probability distribution. As a result, statistical inference was based on untransformed ratios of post-treatment to pre-treatment DNAPL concentrations, with the ratios calculated for pre- and post-treatment samples collected from collected samples at similar depths.

It should be noted that inference assumed independence among sample. This assumption is likely not met due to spatial correlation in the vertical direction. Based on data collected during site characterization, it was determined that there was no spatial correlation in the horizontal direction at distances expected between samples taken in adjacent sub-plots.

Regardless of whether the hypothesis test decided that more or less than 90% of the DNAPL was removed or destroyed, an estimate of reduction/destruction achieved was also of interest. These estimates took the form of confidence intervals for the percent reduction in DNAPL levels due to each technology. Confidence intervals were calculated for the entire plot and separately for each of four geologic strata: vadose zone, upper sand unit, middle fine-grain unit, and lower sand unit. Several confidence levels were used to show the relationship between confidence and interval size.

The statistical inference discussed above was designed to estimate the reduction in total DNAPL in each test plot. It was also of interest to estimate the reduction in free-phase DNAPL in each test plot. When DNAPL concentrations exceed 300 mg/kg, some of the DNAPL will remain in free-phase form. To estimate the reduction in free-phase DNAPL, the following protocol was used:

- Any location for which both pre- and post-treatment DNAPL concentrations were less than 300 were removed;
- The amount of free-phase DNAPL was estimated by subtracting 300 from the observed DNAPL concentration for each sample;
- The value of any free-phase DNAPL concentration that was less than zero was replaced with a value of zero;
- Statistical hypothesis tests were performed and confidence intervals were calculated as described above, using the ratio of post-treatment free-phase DNAPL concentration to pre-treatment free-phase DNAPL concentration.

#### A.1.3.2 Pairwise Comparison Results

Tables A.1-9 and A. 1-10 show the results of the statistical analysis for the oxidation test plot and SPH test plot, respectively. The tables contain information for the entire plot as well as for the four geologic strata contained in the test plot. Summary statistics are presented for both pre-treatment and post-treatment samples, the difference between pre- and post-treatment samples, and for percent reduction in TCE concentrations. Confidence intervals are presented for the difference between pre- and post-treatment TCE concentrations as well as for percent reduction. The results for the hypothesis test to decide whether there was a 90% reduction in DNAPL levels can be obtained from the confidence interval for percent reduction. If the confidence interval contains 90%, the test will not reject the hypothesis test that the reduction is less than or equal to 90%.

Tables A.1-9 and A. 1-10 show that the oxidation treatment was able to reduce TCE concentrations by 77% on average while the SPH treatment was able to reduce TCE concentrations by 83.6% on average. As a result, neither technology was clearly able to exceed the 90% goal. Table A.1-9 and A. 1-10 also show that confidence intervals for the amount and percent of TCE removed are fairly wide. This result is due in large part to a high degree of variability in the data. Statistical analysis also showed that for the SPH treatment, the TCE was removed mainly from the middle fine-grain unit and the lower sand unit, while the oxidation treatment reduced TCE levels equally well in all four units.

Table A.1-11 shows the results of the statistical analysis of free-phase TCE for SPH and oxidation treatments, respectively. Table A.1-11 shows that the reduction in free-phase TCE was 82.7% for the oxidation test plot and 85.2% for the SPH test plot. Both of these results are slightly higher than for overall TCE levels. Again, neither of the methods exceeded the 90% goal. Note that the confidence intervals for percent TCE removed are slightly smaller for the free-phase analysis than for the analysis of total TCE despite a significant decrease in the sample size (due to the removal of data less than 300 ppm). The reason for the smaller size of the confidence interval is that the removal of non-free-phase TCE results also reduced the variability in the data.

**Table A.1-9: Summary of Statistical Analysis of TCE Concentrations in the Oxidation Test Plot**

			Entire Plot				Vadose Zone				Oxidation Plot			
			N	267	41	109	49	USU	MFGU	LSU				
Pre-Treatment TCE Concentrations	Mean	939.9		0.7		144.5		1,722.8		2,216.8				
	Sid Dev	3,154.0		1.4		652.5		5,189.7		3,979.9				
	N	265		41		108		48		68				
Post-Treatment TCE Concentrations	Mean	197.4		0.4		7.9		443.9		443.2				
	Sid Dev	952.6		0.4		27.8		1,596.5		1,264.9				
	N	260		41		108		46		65				
Differences of Pre and Post Treatment TCE Concentrations	Mean	723.9		0.3		136.0		1,349.1		1,714.9				
	Sid Dev	2,910.3		1.5		656.8		5,109.0		3,606.1				
	95% CI for Mean	(368.5, 1,079.3)		(-0.2, 0.8)		(10.7, 261.3)		(-168.1, 2,866.3)		(821.3, 2,608.4)				
	90% CI for Mean	(426.0, 1,021.9)		(-0.1, 0.7)		(31.1, 240.8)		(84.0, 2,614.2)		(968.4, 2,461.4)				
	85% CI for Mean	(463.3, 984.5)		(0.0, 0.6)		(44.3, 227.6)		(245.9, 2,452.3)		(1,063.2, 2,366.6)				
	80% CI for Mean	(492.0, 955.8)		(0.0, 0.6)		(54.5, 217.5)		(369.3, 2,328.8)		(1,135.7, 2,294.1)				
% Reduction	Average	77.0%		44.6%		94.1%		78.3%		77.4%				
	95% Confidence Level	(39.2, 114.8)		(-21.5, 110.8)		(7.4, 180.8)		(-9.8, 166.4)		(37.0, 117.7)				
	90% Confidence Level	(45.3, 108.7)		(-10.5, 99.8)		(21.5, 166.7)		(4.9, 151.7)		(43.7, 111.0)				
	85% Confidence Level	(49.3, 104.8)		(-3.4, 92.7)		(30.7, 157.5)		(14.3, 142.3)		(48.0, 106.8)				
	80% Confidence Level	(52.4, 101.7)		(2.0, 87.3)		(37.7, 150.5)		(21.4, 135.2)		(51.2, 103.5)				

**Table A.1-10: Summary of Statistical Analysis of TCE Concentrations in the SPH Test Plot**

			SPH Plot			SPH Plot		
			Entire Plot	Vadose Zone	USU	MFRGU	LSU	
Pre-Treatment TCE Concentrations	N	256	44	93	42	77		
	Mean	1,281.6	2.6	61.4	1,358.3	3,444.4		
	Std Dev	5,332.7	7.6	277.2	3,540.2	9,002.9		
Post-Treatment TCE Concentrations	N	257	46	90	43	78		
	Mean	154.6	6.7	102.8	372.6	181.5		
	Std Dev	514.4	14.5	467.6	1,004.2	182.8		
Differences of Pre and Post Treatment	N	243	44	83	42	74		
	Mean	1,070.9	-4.4	-63.7	978.4	3,035.5		
	Std Dev	5,223.8	16.8	535.6	3,695.1	8,740.2		
95% CI for Mean TCE Concentrations	(410.8, 1,731.0)	(-9.5, 0.7)	(-180.7, 53.2)	(-173.1, 2,129.8)	(1,010.5, 5,060.4)			
	(517.6, 1,624.2)	(-8.7, -0.2)	(-161.6, 34.1)	(18.8, 1,937.9)	(1,342.8, 4,728.2)			
	(587.0, 1,554.8)	(-8.1, -0.7)	(-149.2, 21.7)	(141.9, 1,814.8)	(1,557.3, 4,513.6)			
% Reduction	80% CI for Mean	(640.3, 1,501.5)	(-7.7, -1.1)	(-139.7, 12.2)	(235.7, 1,721.0)	(1,721.5, 4,349.5)		
	Average	83.6%	-168.6%	-103.8%	72.0%	88.1%		
	95% Confidence Level	(32.1, 135.1)	(-363.8, 26.5)	(-294.2, 86.6)	(-12.7, 156.8)	(29.3, 146.9)		
	90% Confidence Level	(40.4, 126.7)	(-331.3, -5.9)	(-263.0, 55.5)	(1.4, 142.7)	(39.0, 137.3)		
	85% Confidence Level	(45.8, 121.3)	(-310.5, -26.8)	(-242.8, 35.3)	(10.4, 133.6)	(45.2, 131.0)		
	80% Confidence Level	(50.0, 117.2)	(-294.6, -42.7)	(-227.4, 19.9)	(17.4, 126.7)	(50.0, 126.3)		

**Table A.1-11: Summary of Statistical Analysis of Free-Phase TCE in the Oxidation Test Plot**

		Oxidation Plot	SPH Plot
Pre-Treatment TCE Concentrations	N	54	55
	Mean	4,387.2	5,847.3
	Std Dev	5,892.0	10,355.5
Post-Treatment TCE Concentrations	N	51	53
	Mean	960.9	549.9
	Std Dev	2,011.7	1,040.1
Differences of Pre and Post Treatment TCE Concentrations	N	49	53
	Mean	3,627.1	4,981.0
	Std Dev	5,921.5	10,345.9
	95% CI for Mean	(1,926.2, 5,327.9)	(2,129.3, 7,832.7)
	90% CI for Mean	(2,208.2, 5,045.9)	(2,601.1, 7,360.9)
	85% CI for Mean	(2,389.5, 4,864.6)	(2,904.6, 7,057.4)
	80% CI for Mean	(2,527.8, 4,726.3)	(3,136.3, 6,825.7)
	Average	82.7%	85.2%
% Reduction	95% Confidence Level	(43.9, 121.4)	(36.4, 134.0)
	90% Confidence Level	(50.3, 115.0)	(44.5, 125.9)
	85% Confidence Level	(54.5, 110.9)	(49.7, 120.7)
	80% Confidence Level	(57.6, 107.7)	(53.6, 116.7)

## **A.2 Sample Collection and Extraction Methods**

This section describes the modification made to the EPA standard methods to address the lithologic heterogeneities and extreme variability of the contaminant distribution expected in the DNAPL source region at Launch Complex 34. Horizontal variability was addressed by collecting a statistically determined number (12) of soil cores in the Oxidation Plot. The vertical variability at each soil coring location was addressed with this modified sampling and extraction procedure, which involved extraction of much larger quantities of soil in each extracted sample, as well as allowed collection and extraction of around 300 samples in the field per event. This extraction allowed the extraction and analysis of the entire vertical column of soil at a given coring location.

### **A.2.1 Soil Sample Collection (Modified ASTM D4547-91) (1997b)**

The soil samples collected before and after the demonstration were sampled using a stainless steel sleeve driven into the subsurface by a cone penetrometer test (CPT) rig. After the sleeve had been driven the required distance, it was brought to the surface and the soil sample was examined and characterized for lithology. One quarter of the sample was sliced from the core and placed into a pre-weighed 500-mL polyethylene container. At locations where a field duplicate sample was collected, a second one-quarter sample was split from the core and placed into another pre-weighed 500-mL polyethylene container. The remaining portion of the core was placed into a 55-gallon drum and disposed of as waste. The samples were labeled with the date, time, and sample identification code, and stored on ice at 4°C until they were brought inside to the on-site laboratory for the extraction procedure.

After receiving the samples from the drilling activities, personnel staffing the field laboratory performed the methanol extraction procedure as outlined in Section A.2.2 of this appendix. The amount of methanol used to perform the extraction technique was 250 mL. The extraction procedure was performed on all of the primary samples collected during drilling activities and on 5% of the field duplicate samples collected for quality assurance. Samples were stored at 4°C until extraction procedures were performed. After the extraction procedure was finished, the soil samples were dried in an oven at 105°C and the dry weight of each sample was determined. The samples were then disposed of as waste. The remaining three-quarter section of each core previously stored in a separate 500-mL polyethylene bottle were archived until the off-site laboratory had completed the analysis of the methanol extract. The samples were then disposed of in an appropriate manner.

### **A.2.2 Soil Extraction Procedure (Modified EPA SW846-Method 5035)**

After the soil samples were collected from the drilling operations, samples were placed in pre-labeled and pre-weighed 500-mL polyethylene containers with methanol and then stored in a refrigerator at 4°C until the extraction procedure was performed. Extraction procedures were performed on all of the “A” samples from the outdoor and indoor soil sampling. Extraction procedures also were performed on 5% of the duplicate (or “B”) samples to provide adequate quality assurance/quality control (QA/QC) on the extraction technique.

Extreme care was taken to minimize the disturbance of the soil sample so that loss of volatile components was minimal. Nitrile gloves were worn by field personnel whenever handling sample cores or pre-weighed sample containers. A modification of EPA SW846-Method 5035 was used to procure the cored samples in the field. Method 5035 lists different procedures for processing samples that are expected to contain low concentrations (0.5 to 200 µg/kg) or high concentrations

(>200 µg/kg) of volatile organic compounds (VOCs). Procedures for high levels of VOCs were used in the field because those procedures facilitated the processing of large-volume sample cores collected during soil sampling activities.

Two sample collection options and corresponding sample purging procedures are described in Method 5035; however, the procedure chosen for this study was based on collecting approximately 150 to 200 g of wet soil sample in a pre-weighed bottle that contains 250 mL of methanol. A modification of this method was used in the study, as described by the following procedure:

- The 150 to 200 g wet soil sample was collected and placed in a pre-weighed 500 mL polypropylene bottle. After capping, the bottle was reweighed to determine the wet weight of the soil. The container was then filled with 250 ml of reagent grade methanol. The bottle was weighed a third time to determine the weight of the methanol added. The bottle was marked with the location and the depth at which the sample was collected.
- After the containers were filled with methanol and the soil sample they were placed on an orbital shaker table and agitated for approximately 30 min.
- Containers were removed from the shaker table and reweighed to ensure that no methanol was lost during the agitation period. The containers were then placed upright and suspended soil matter was allowed to settle for approximately 15 min.
- The 500 mL containers were then placed in a floor-mounted centrifuge. The centrifuge speed was set at 3,000 rpm and the samples were centrifuged for 10 min.
- Methanol extract was then decanted into disposable 20-mL glass volatile organic analysis (VOA) vials using 10-mL disposable pipettes. The 20-mL glass VOA vials containing the extract then were capped, labeled, and stored in a refrigerator at 4°C until they were shipped on ice to the analytical laboratory.
- Methanol samples in VOA vials were placed in ice chests and maintained at approximately 4°C with ice. Samples were then shipped with properly completed chain-of-custody forms and custody seals to the subcontracted off-site laboratory.
- The dry weight of each of the soil samples was determined gravimetrically after decanting the remaining solvent and drying the soil in an oven at 105°C. Final concentrations of VOCs were calculated per the dry weight of soil.

Three potential concerns existed with the modified solvent extraction method. The first concern was that the United States Environmental Protection Agency (U.S. EPA) had not formally evaluated the use of methanol as a preservative for VOCs. However, methanol extraction often is used in site characterization studies, so the uncertainty in using this approach was reasonable. The second concern was that the extraction procedure itself would introduce a significant dilution factor that could raise the method quantitation limit beyond that of a direct purge-and-trap procedure. The third concern was that excess methanol used in the extractions would likely fail the ignitability characteristic, thereby making the unused sample volume a hazardous waste. During characterization activities, the used methanol extract was disposed of as hazardous waste into a 55-gallon drum. This methanol extraction method was tested during preliminary site characterization activities at this site (see Appendix G, Table G-1) and, after a few refinements,

was found to perform acceptably in terms of matrix spike recoveries. Spiked TCE recoveries in replicate samples ranged from 72 to 86%.

The analytical portion of Method 5035 describes a closed-system purge-and-trap process for use on solid media such as soils, sediments, and solid waste. The purge-and-trap system consists of a unit that automatically adds water, surrogates, and internal standards to a vial containing the sample. Then the process purges the VOCs using an inert gas stream while agitating the contents of the vial, and finally traps the released VOCs for subsequent desorption into a gas chromatograph (GC). STL Environmental Services performed the analysis of the solvent extraction samples. Soil samples were analyzed for organic constituents according to the parameters summarized in Table A.2-1. Laboratory instruments were calibrated for VOCs listed under U.S. EPA Method 601 and 602. Samples were analyzed as soon as was practical and within the designated holding time from collection (14 days). No samples were analyzed outside of the designated 14-day holding time.

**Table A.2-1. Soil Sampling and Analytical Parameters**

Analytes	Extraction Method	Analytical Method	Sample Holding Time	Matrix
VOCs <sup>(a)</sup>	SW846-5035	SW846-8260	14 days	Methanol

(a) EPA 601/602 list.

### A.3 List of Standard Sample Collection and Analytical Methods

**Table A.3-1. Sample Collection Procedures**

Measurements	Task/Sample Collection Method	Equipment Used
<b>Primary Measurements</b>		
CVOCs	Soil sampling/ Mod. <sup>(a)</sup> ASTM D4547-91 (1997c)	Stainless steel sleeve 500-mL plastic bottle
CVOCs	Groundwater sampling/ Mod. <sup>(a)</sup> ASTM D4448-85a (1997a)	Peristaltic pump Teflon™ tubing
<b>Secondary Measurements</b>		
TOC	Soil sampling/ Mod. <sup>(a)</sup> ASTM D4547-91 (1997c)	Stainless steel sleeve
Field parameters <sup>(b)</sup> TOC BOD Inorganics—cations Inorganics—anions TDS Alkalinity	Groundwater sampling/ Mod. <sup>(a)</sup> ASTM D4448-85a (1997a)	Peristaltic pump Teflon™ tubing
Hydraulic conductivity	Hydraulic conductivity/ ASTM D4044-96 (1997d)	Winsitu® troll Laptop computer
Groundwater level	Water levels	Water level indicator
CVOCs	Vapor Sampling/Tedlar Bag, TO-14	Vacuum Pump

(a) Modifications to ASTM are detailed in Appendix B.

(b) Field parameters include pH, ORP, temperature, DO, and conductivity. A flowthrough well will be attached to the peristaltic pump when measuring field parameters.

ASTM = American Society for Testing and Materials.

**Table A.3-2. Sample Handling and Analytical Procedures**

Measurements	Matrix	Amount Collected	Analytical Method	Maximum Holding Time <sup>(a)</sup>	Sample Preservation <sup>(b)</sup>	Sample Container	Sample Type
<i>Primary Measurements</i>							
CVOCs	Soil	250 g	Mod. EPA 8260 <sup>(c)</sup>	14 days	4°C	Plastic	Grab
CVOCs	Groundwater	40-mL × 3	EPA 8260 <sup>(d)</sup>	14 days	4°C, pH < 2 HCl	Glass	Grab
<i>Secondary Measurements</i>							
CVOCs	Groundwater	40-mL × 3	EPA 8021/8260 <sup>(d)</sup>	14 days	4°C, pH < 2 HCl	Glass	Grab
CVOCs	Vapor	1 L	TO-14	14 days	NA	Tedlar™ Bag	Grab
pH	Soil	50 g	Mod. EPA 9045c	7 days	None	Plastic	Grab
pH	Groundwater	50 mL	EPA 150.1	1 hour	None	Plastic	Grab
TOC	Soil	20 g	SW 9060	28 days	None	Plastic	Grab
TOC	Groundwater	125 mL	EPA 415.1	28 days	4°C, pH < 2 H <sub>2</sub> SO <sub>4</sub>	Plastic	Grab
BOD	Groundwater	1,000 mL	EPA 405.1	48 hours	4°C	Plastic	Grab
Hydraulic conductivity	Aquifer	NA	ASTM D4044-96 (1997d)	NA	NA	NA	NA
Inorganics—cations <sup>(e)</sup>	Groundwater	100 mL	SW 6010	28 days	4°C, pH<2, HNO <sub>3</sub>	Plastic	Grab
Inorganics—anions <sup>(e)</sup>	Groundwater	50 mL	EPA 300.0	28 days	4°C	Plastic	Grab
TDS	Groundwater	500 mL	EPA 160.1	7 days	4°C	Plastic	Grab
Alkalinity	Groundwater	200 mL	EPA 310.1	14 days	4°C	Plastic	Grab
Water levels	Aquifer	NA	Water level from the top of well casing	NA	NA	NA	NA

- (a) Samples will be analyzed as soon as possible after collection. The times listed are the maximum holding times which samples will be held before analysis and still be considered valid. All data obtained beyond the maximum holding times will be flagged.
- (b) Samples will be preserved immediately upon sample collection, if required.
- (c) Samples will be extracted using methanol on site. For the detailed extraction procedure see Appendix B.
- (d) The off-site laboratory will use EPA 8260.
- (e) Cations include Ca, Mg, Fe, Mn, Na, and K. Anions include Cl, SO<sub>4</sub>, and NO<sub>3</sub>/ NO<sub>2</sub>. HCl = Hydrochloric acid.

NA = Not applicable.

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## **Appendix B. Hydrogeologic Measurements**

## B.1 Performance Monitoring Slug Tests

Slug tests were performed on well clusters BAT-3, BAT-5, and BAT-6 within the in-situ oxidation plot for pre-demonstration, post-demonstration, and the extended monitoring activities. Pre-demonstration tests were completed in August 1999, post-demonstration tests were completed in August 2000, and extended monitoring tests were completed in February 2001. Bat-5 was included because BAT-3S was unavailable during pre-demonstration activities due to the installation of the oxidation system equipment. The tests consisted of placing a pressure transducer and 1.5-inch-diameter by 5-ft-long solid PVC slug within the well. After the water level reached an equilibrium, the slug was removed rapidly. Removal of the slug created approximately 2 ft of change in water level within the well. Water level recovery was then monitored for 5-10 minutes using a TROLL pressure transducer/data logger. The data was then downloaded to a notebook computer.

The recovery rates of the water levels were analyzed with the Bouwer (1989) and Bouwer and Rice (1976) methods for slug tests in unconfined aquifers. Graphs were made showing the changes in water level versus time and curve fitted on a semi-logarithmic graph. The slope of the fitted line then was used in conjunction with the well parameters to provide a value of the permeability of the materials surrounding the well. The results show a good agreement between the replicate tests.

The tests are subject to minor variations. As such, a change of more than a magnitude of order would be required to indicate a change in the permeability of the sediments. Keeping this in mind, the tests showed a negligible change in permeability in most wells as shown on Table 1. The tests in wells BAT-3D and BAT6S may have increased substantially in permeability; although, the response to the slug was poor in these wells.

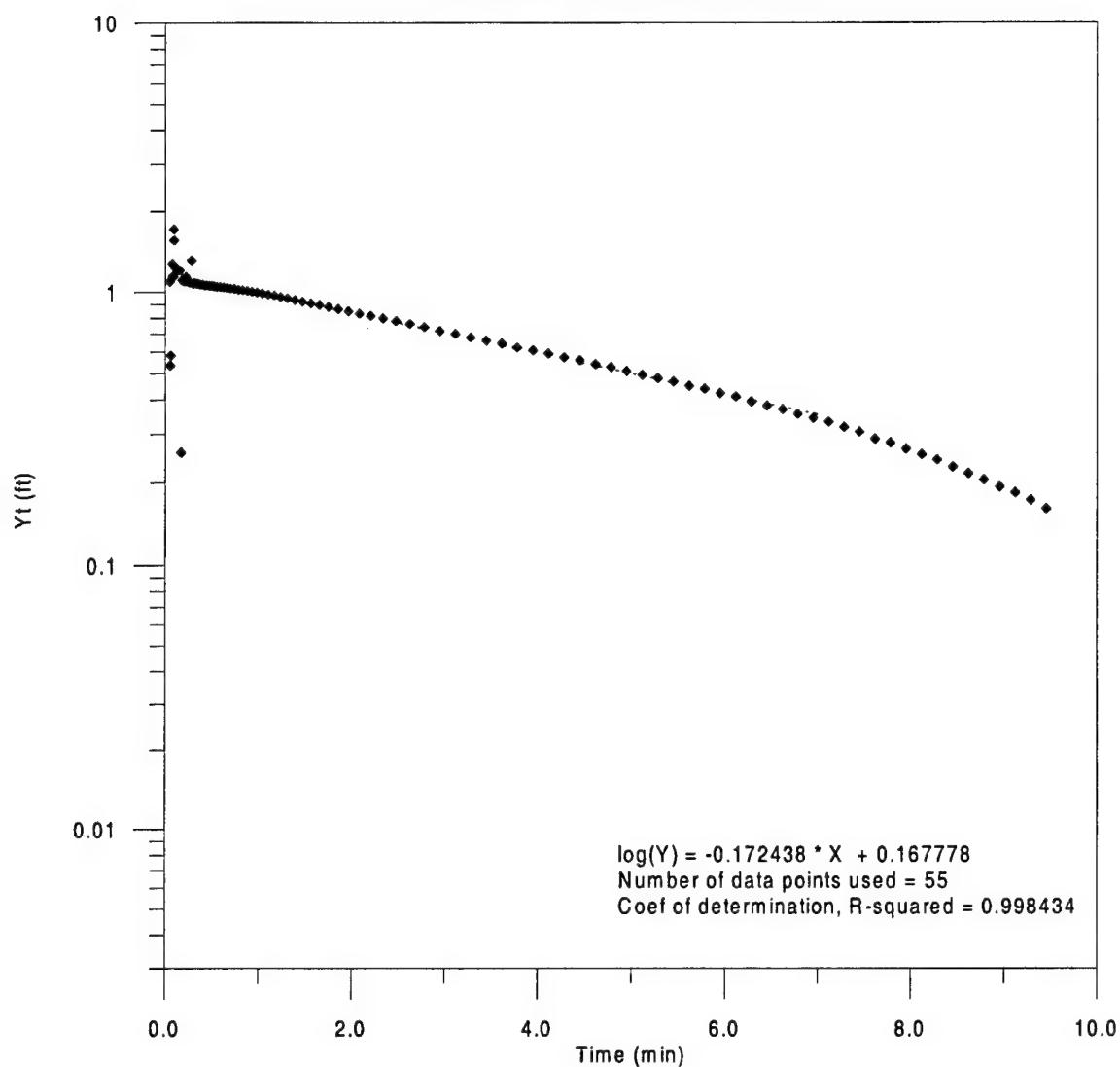
**Table B-1. Slug Test Results in Oxidation Plot.**

Well	Predemo	Postdemo	Ext. Mon.	Change	Response
BAT-3D	1.3	(26.4)	(65.8)	(increase?)	poor
BAT-3I	1.6	2.4	1.4	negligible	excellent
BAT-5I	6.4	1.5	6.2	negligible	fair
BAT-5S	4.0	5.0	1.5	negligible	good
BAT-6D	2.3	1.4	0.4	negligible	good
BAT-6I	1.4	3.7	1.2	negligible	fair
BAT-6S	5.1	(97.3)	(57.2)	(increase?)	poor

Bouwer, H., and R.C. Rice, 1976, A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells, *Water Resources Research*, v.12, n.3, pp. 423-428.

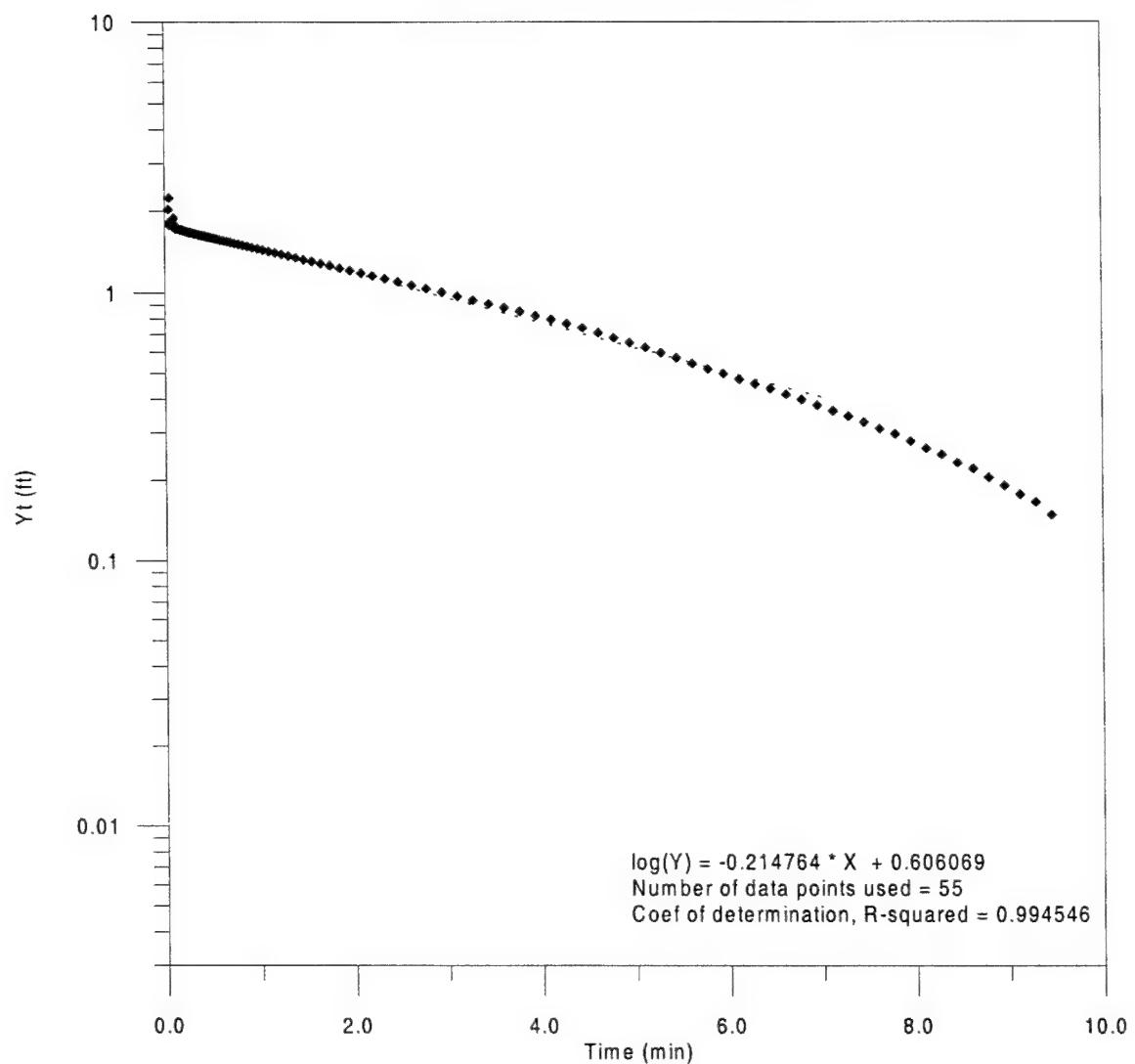
Bouwer, H., 1989, The Bouwer and Rice slug test- an update, *Ground Water*, v. 27, n.3., pp. 304-309.

### Well BAT-3D: Replicate A



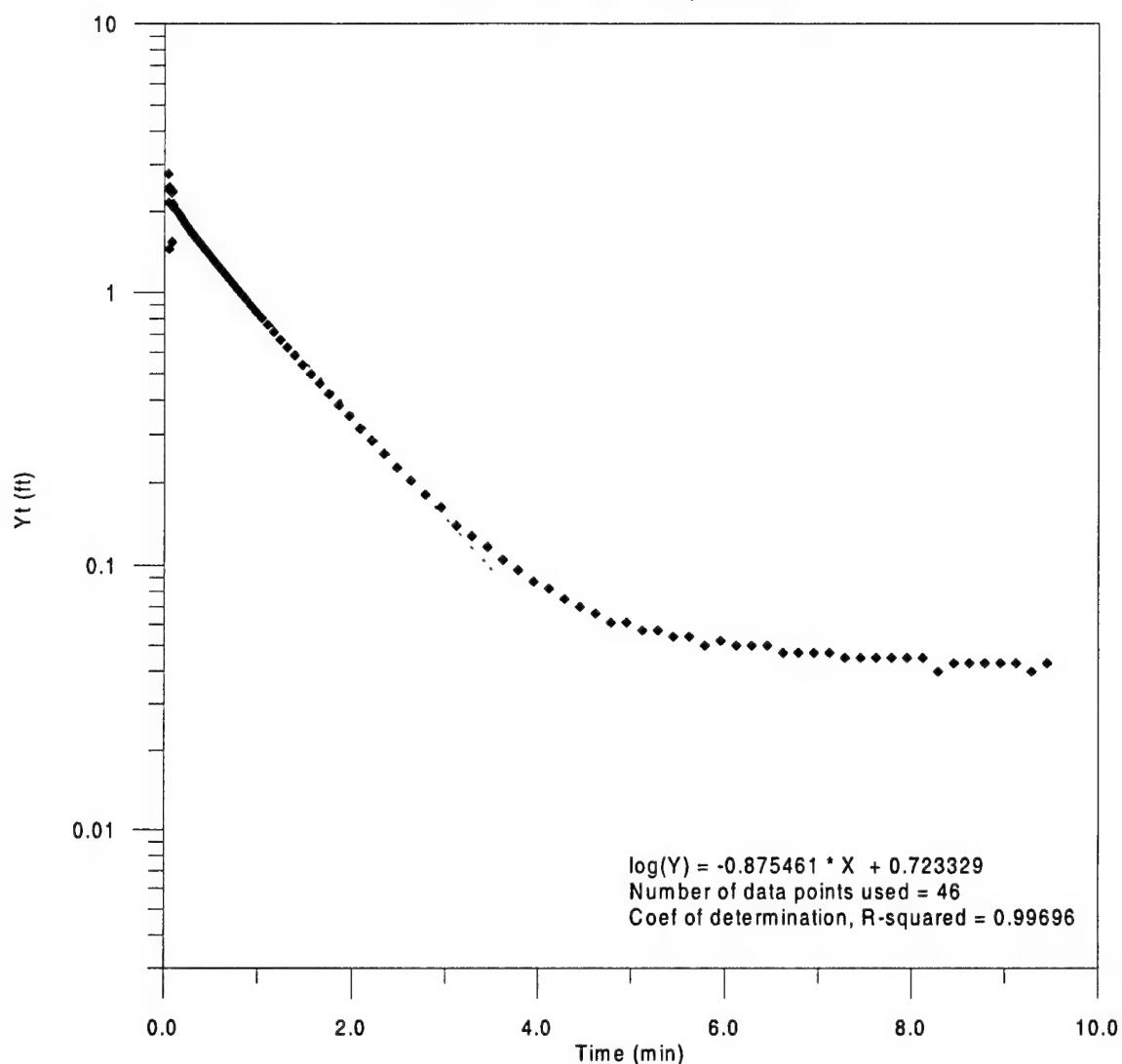
**Pre-demonstration Slug Test Results: Well BAT-3D.**

### Well BAT-3I: Replicate A



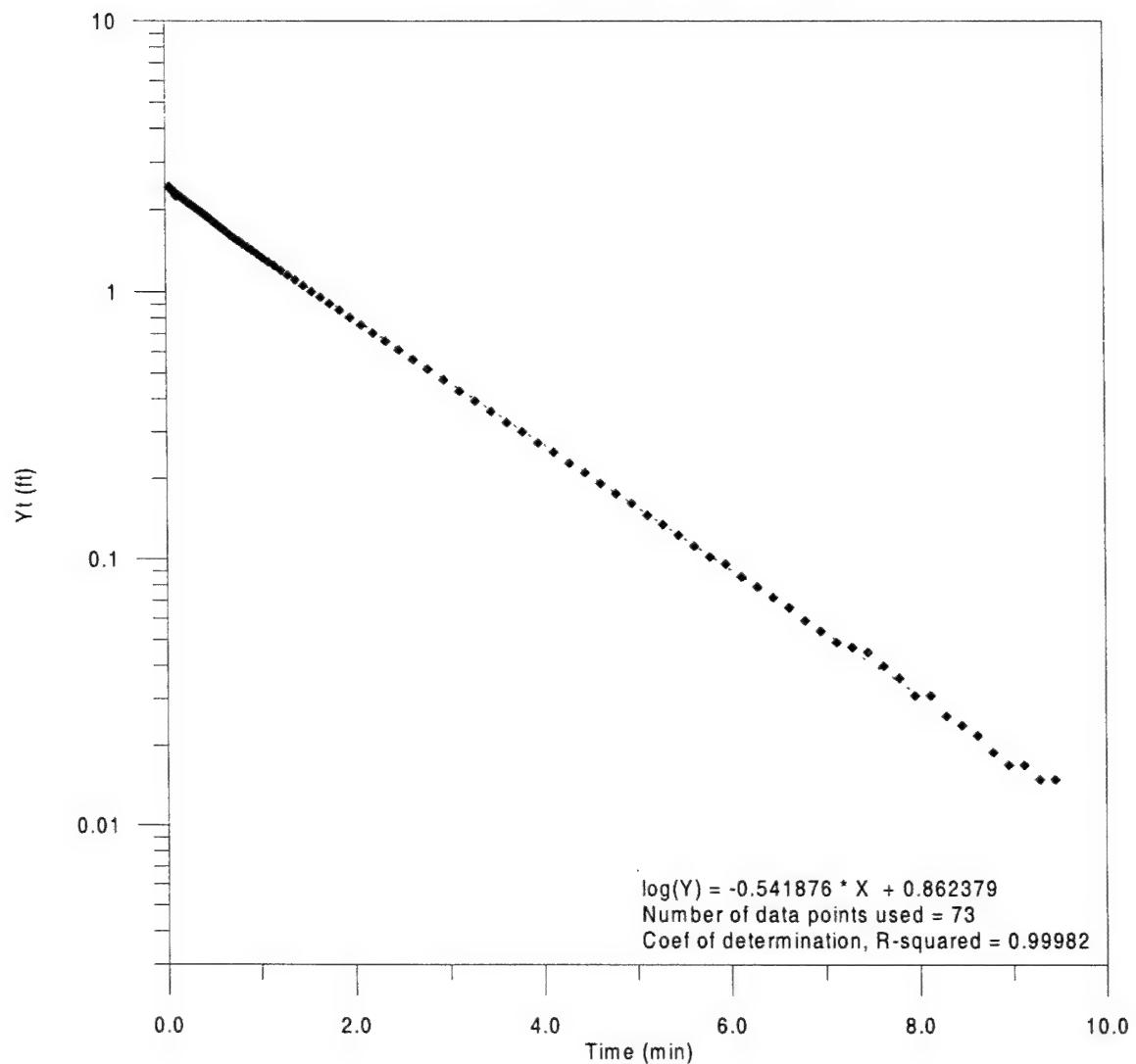
**Pre-demonstration Slug Test Results: Well BAT-3I.**

### Well BAT-5I: Replicate A



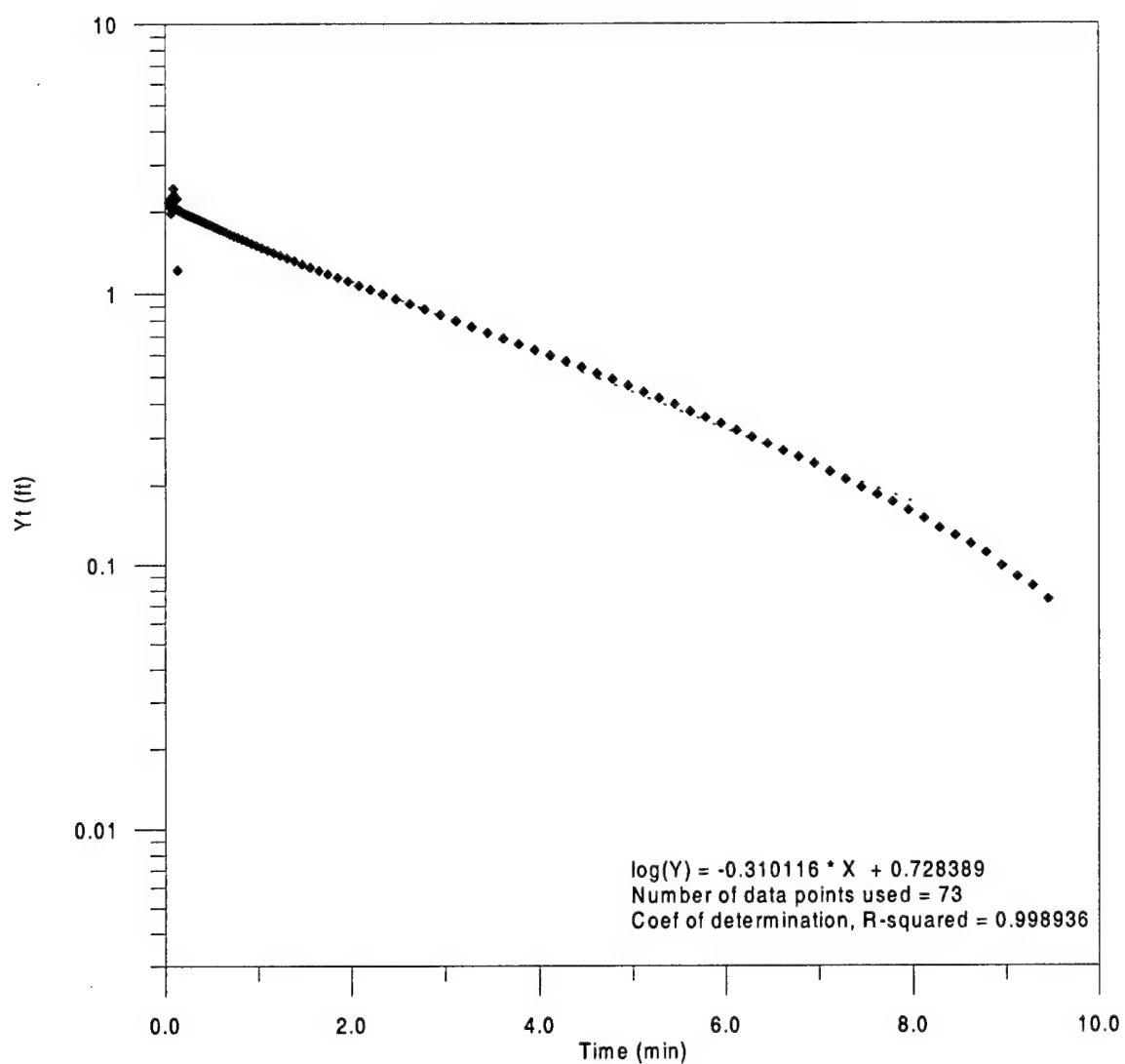
Pre-demonstration Slug Test Results: Well BAT-5I.

### Well BAT-5S: Replicate A



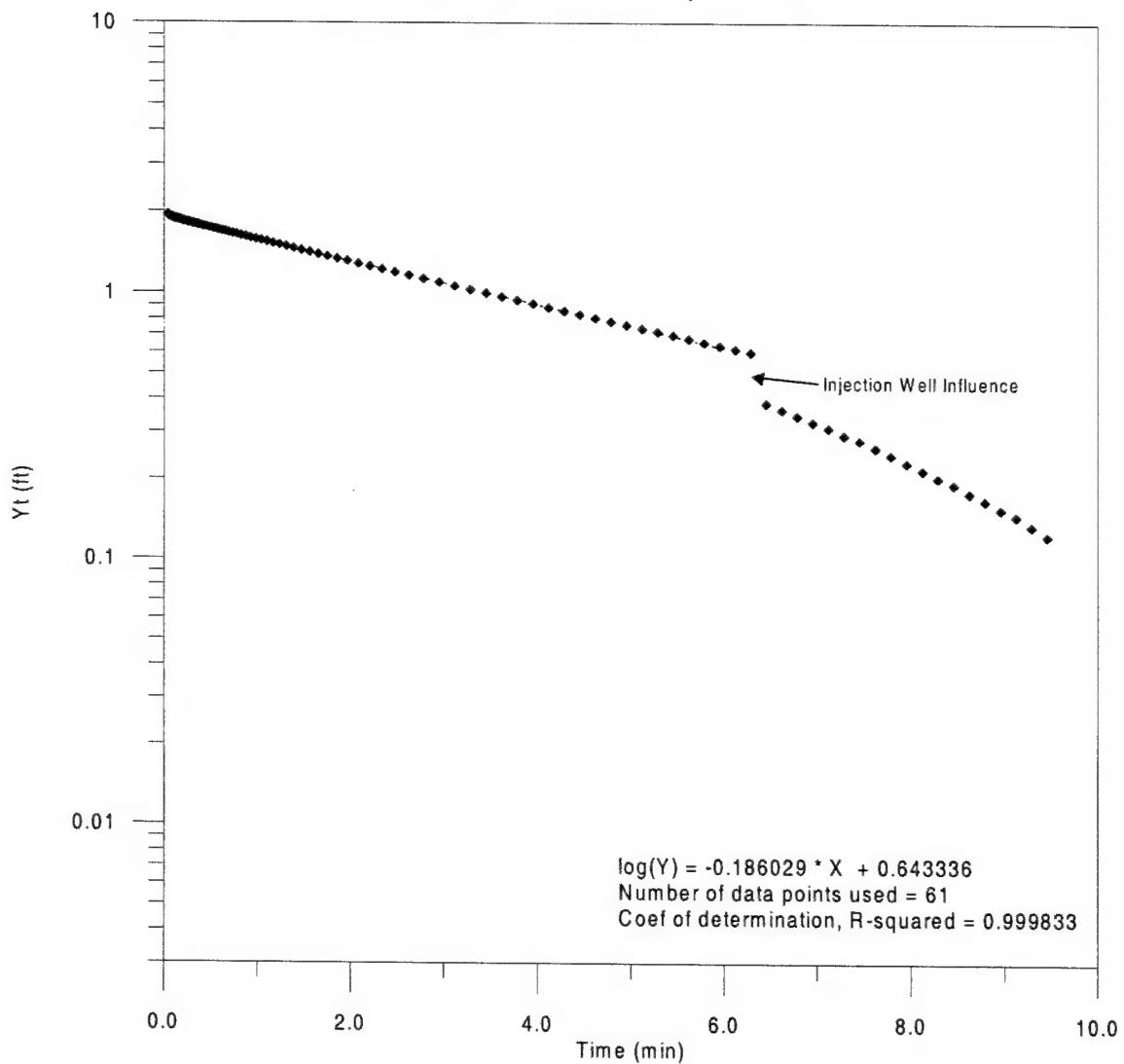
**Pre-demonstration Slug Test Results: Well BAT-5S.**

### Well BAT-6D: Replicate A



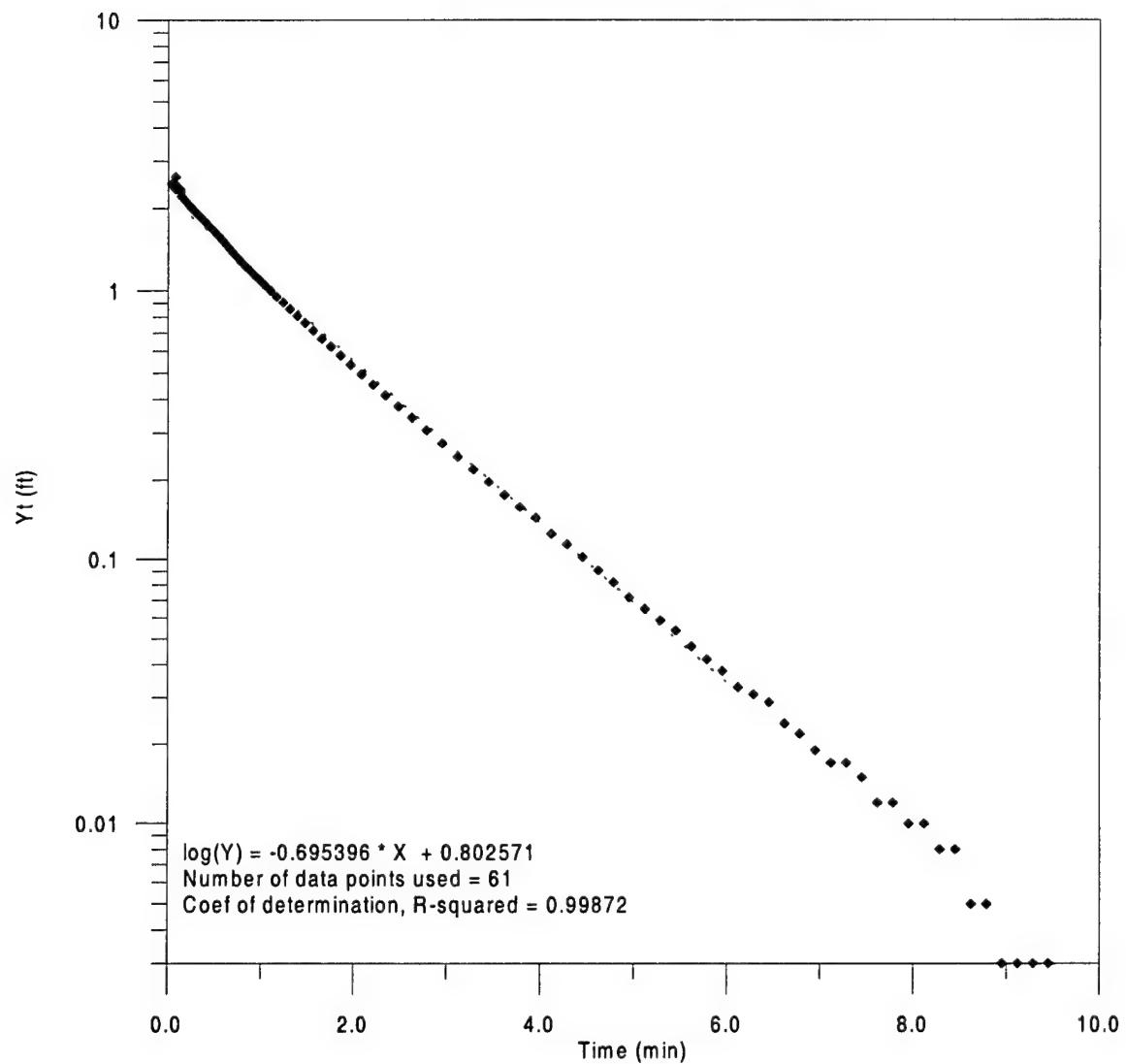
**Pre-demonstration Slug Test Results: Well BAT-6D.**

### Well BAT-6I: Replicate A



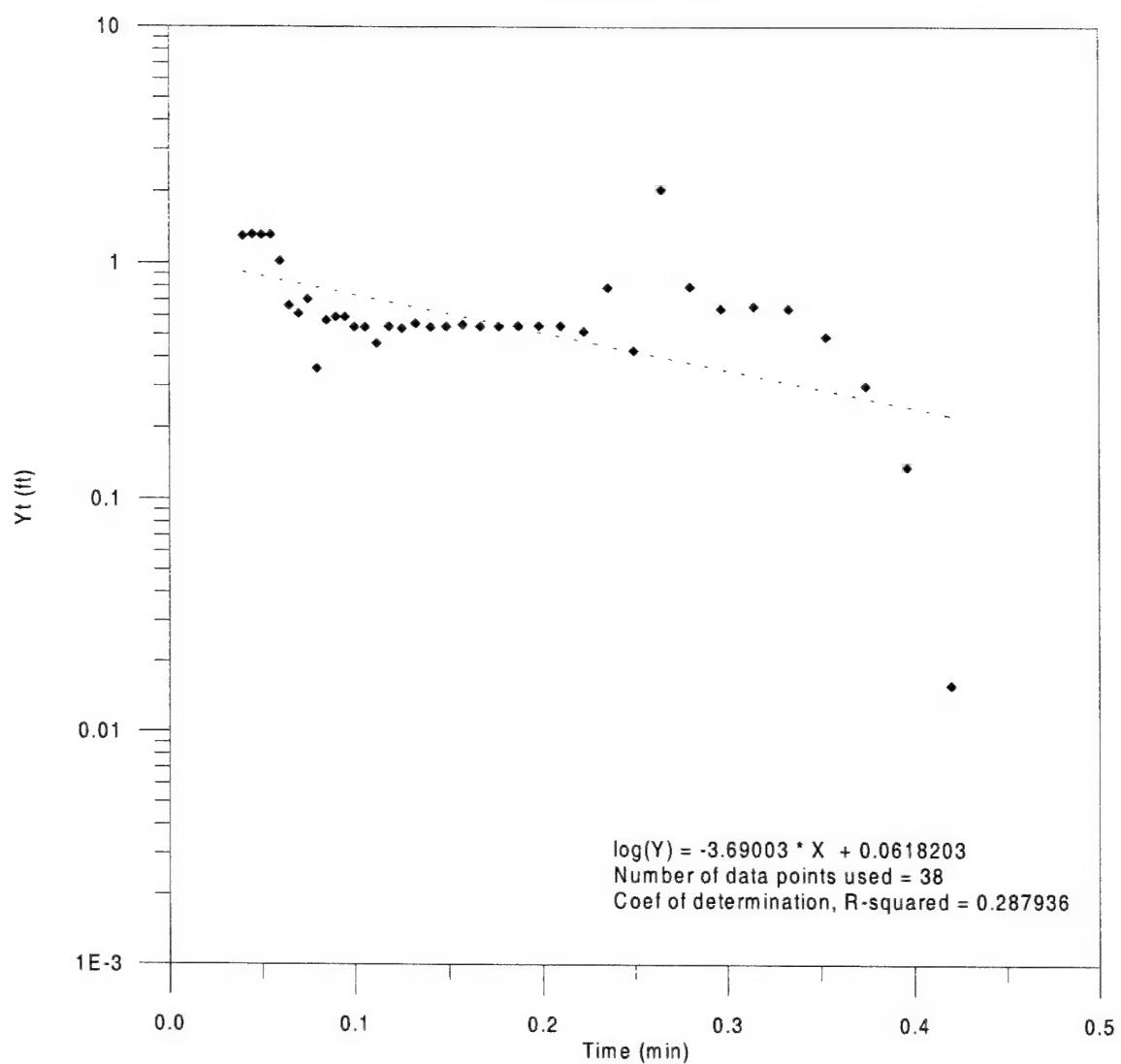
Pre-demonstration Slug Test Results: Well BAT-6I.

### Well BAT-6S: Replicate A



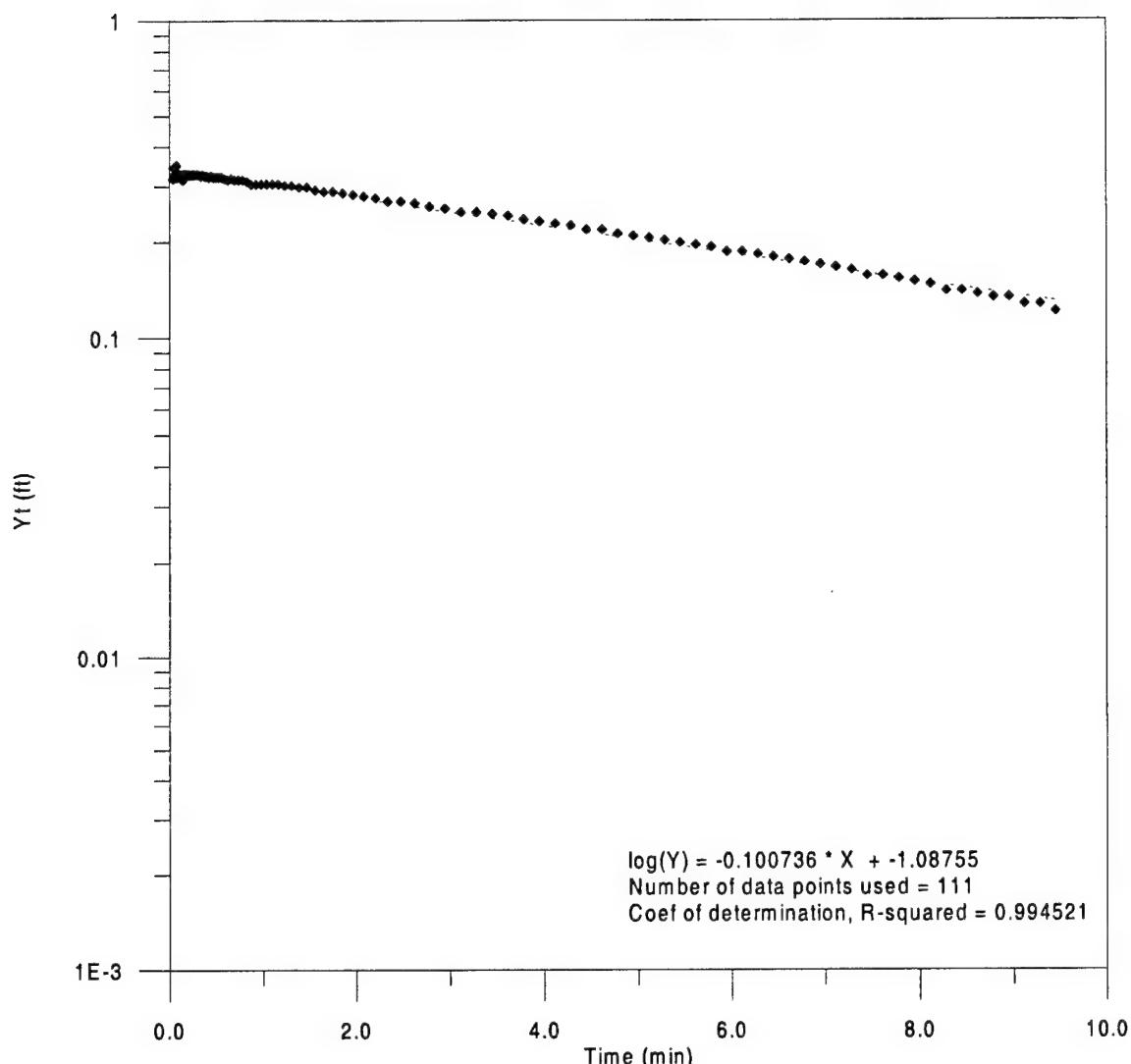
Pre-demonstration Slug Test Results: Well BAT-6S.

### Well BAT-3D



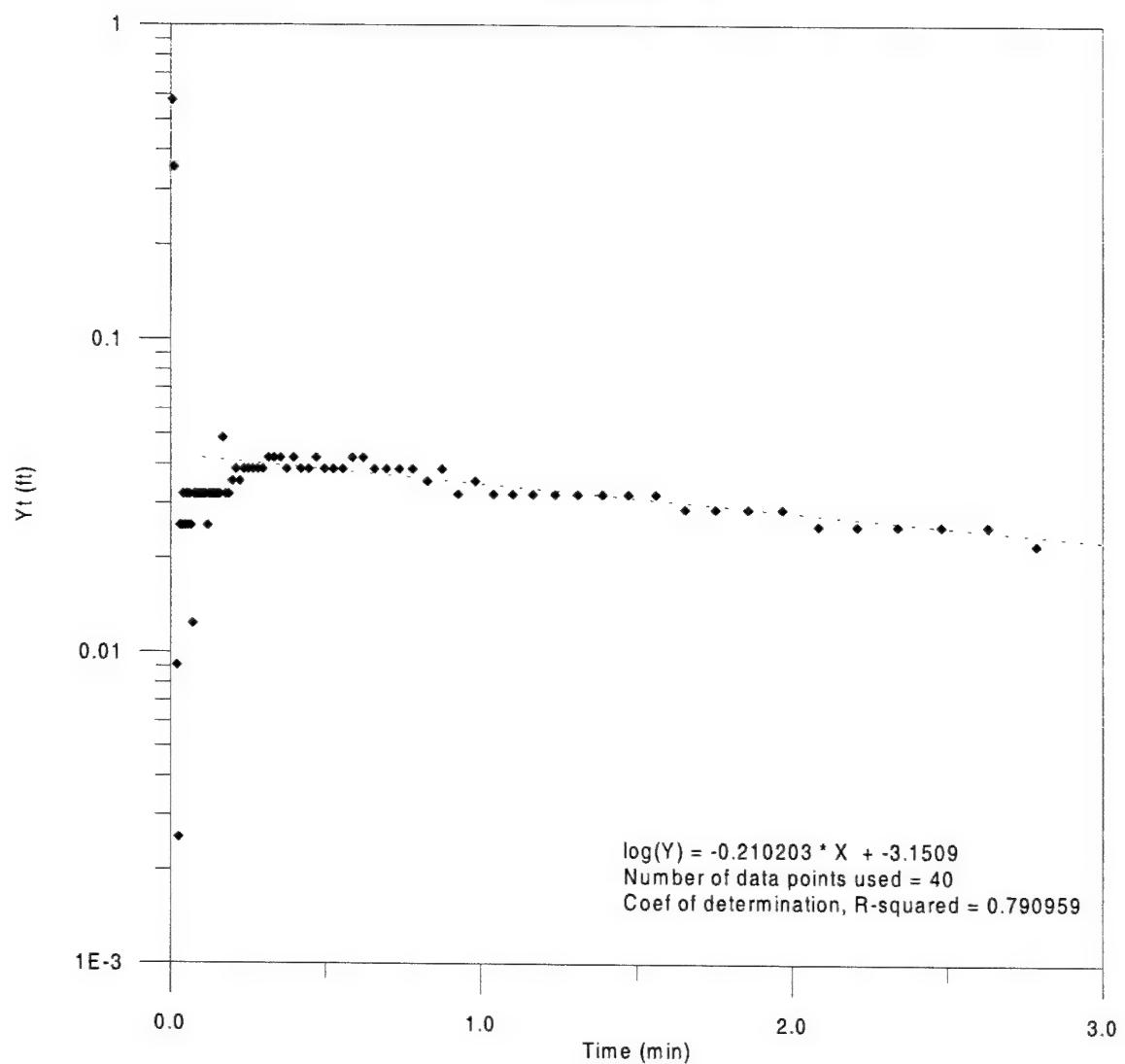
Post-demonstration Slug Test Results: Well BAT-3D.

### Well BAT-3I



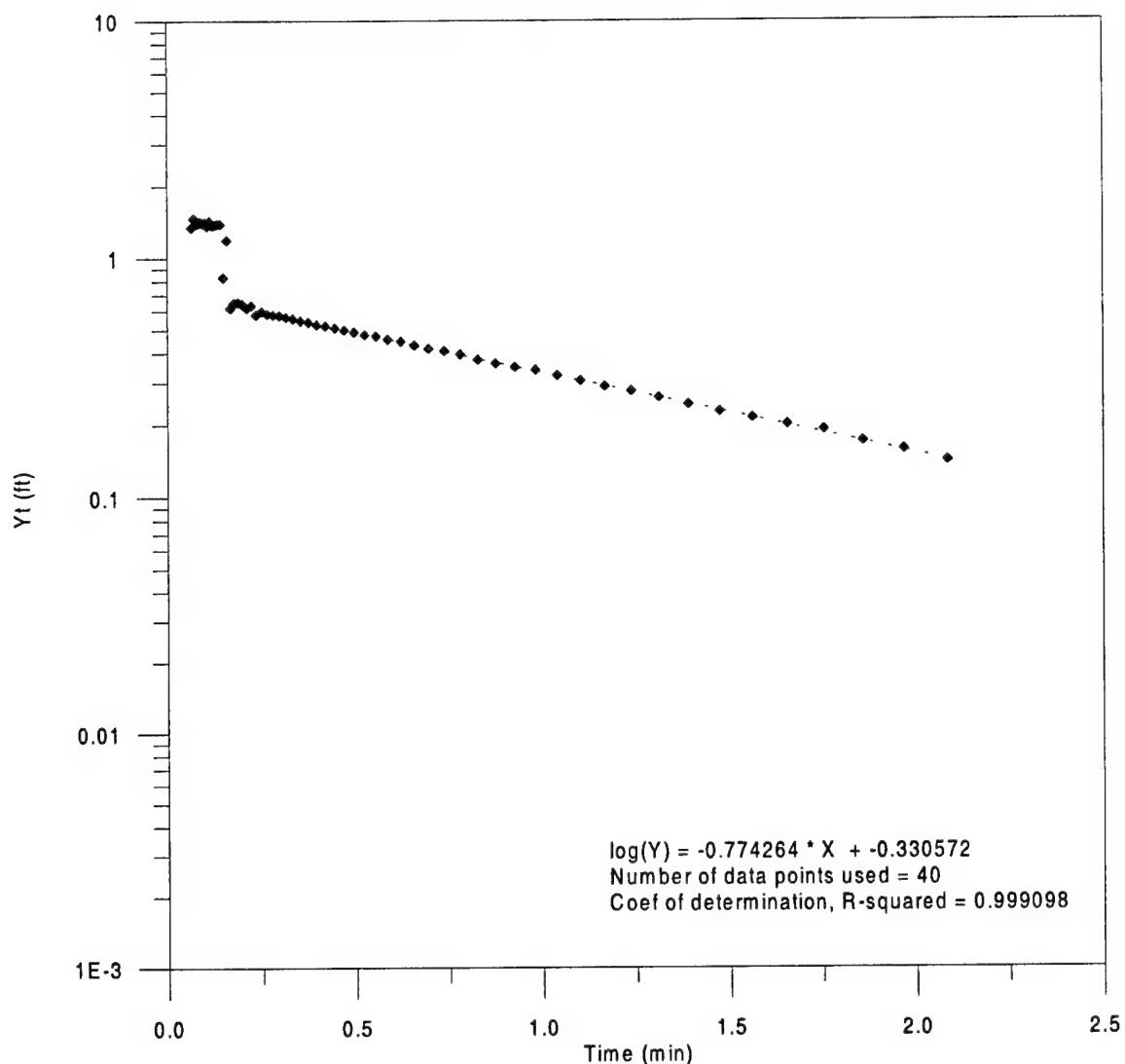
**Post-demonstration Slug Test Results: Well BAT-3I.**

### Well BAT-5I



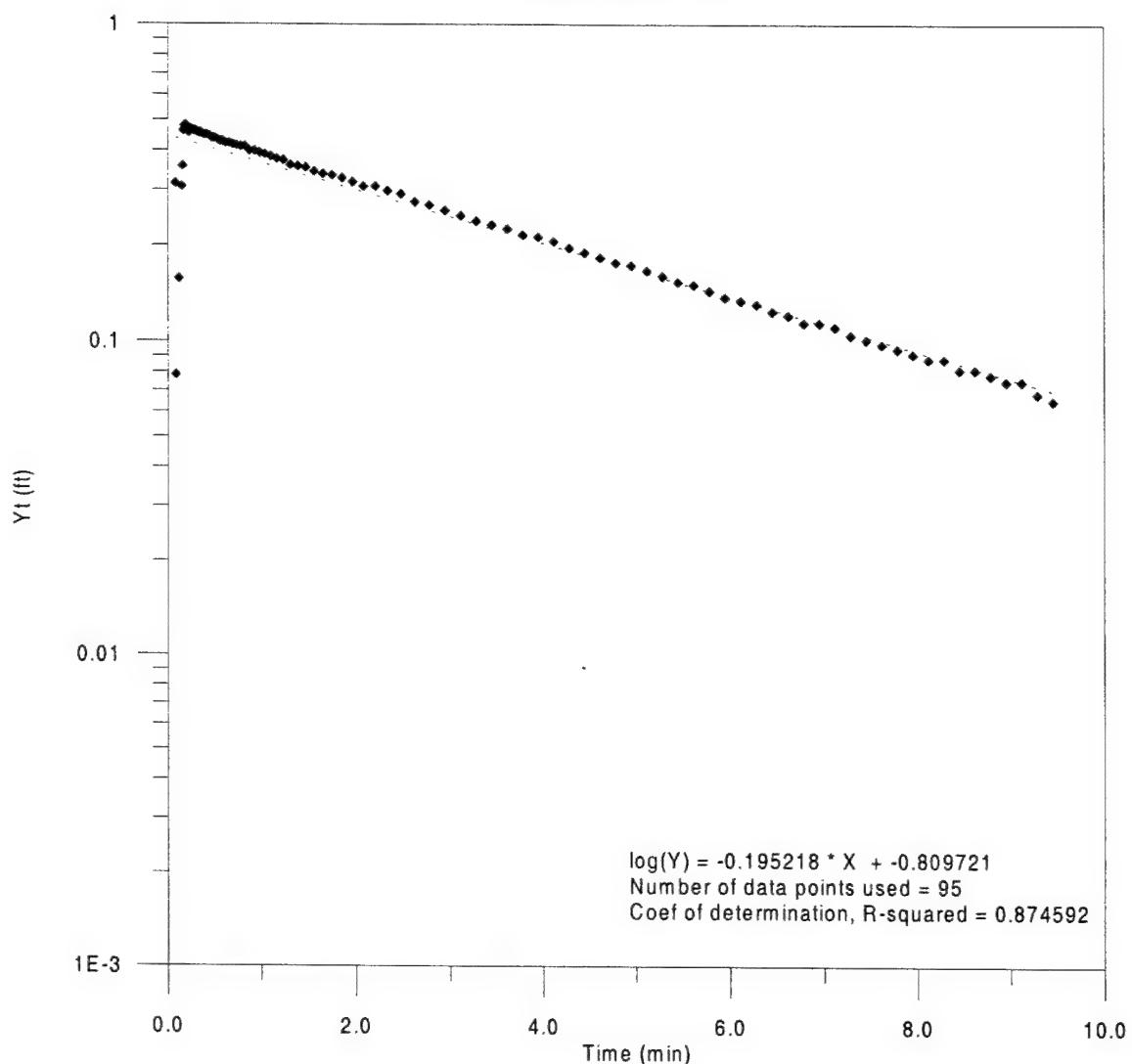
**Post-demonstration Slug Test Results: Well BAT-5I.**

### Well BAT-5S



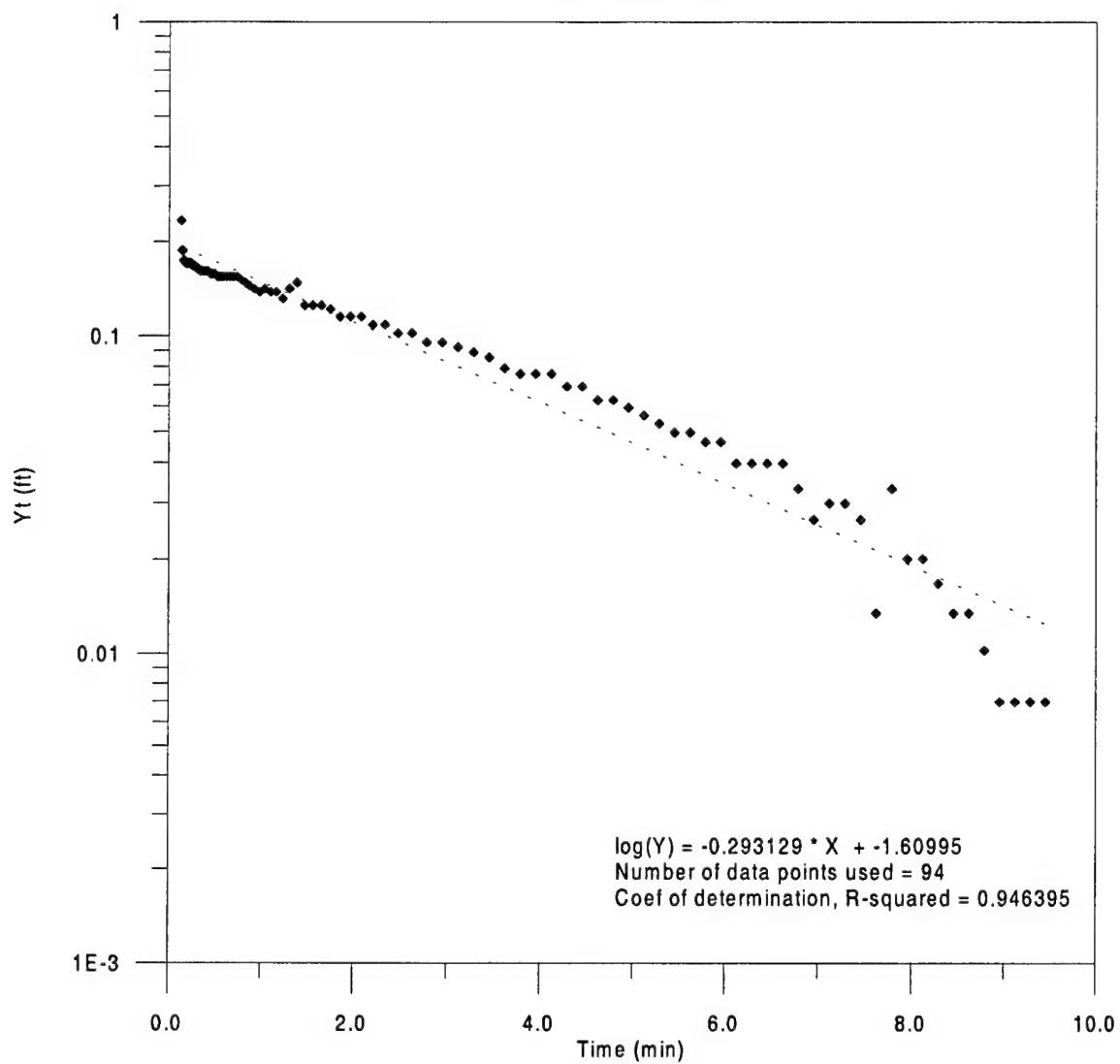
**Post-demonstration Slug Test Results: Well BAT-5S.**

### Well BAT-6D



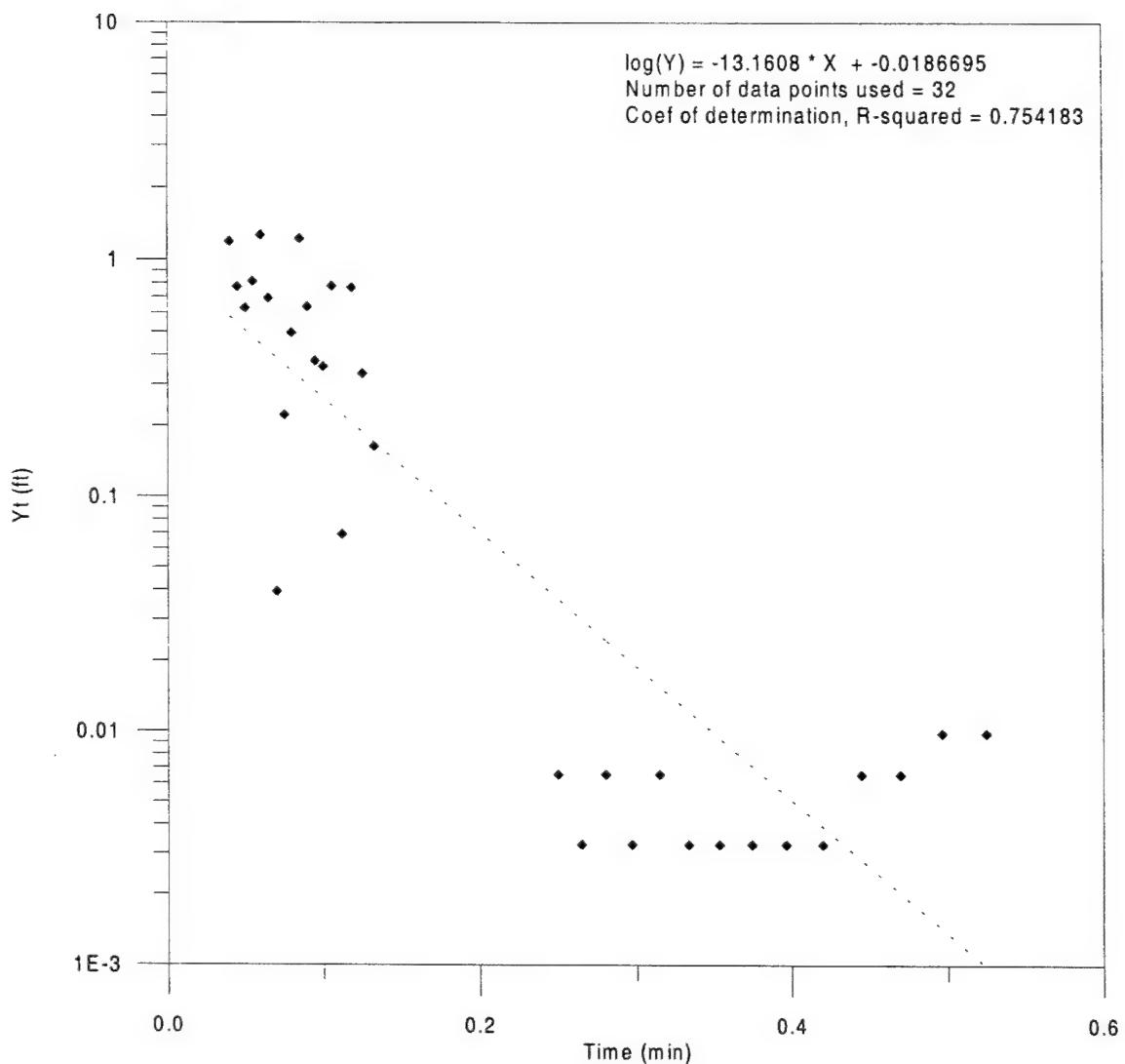
**Post-demonstration Slug Test Results: Well BAT-6D.**

### Well BAT-6I



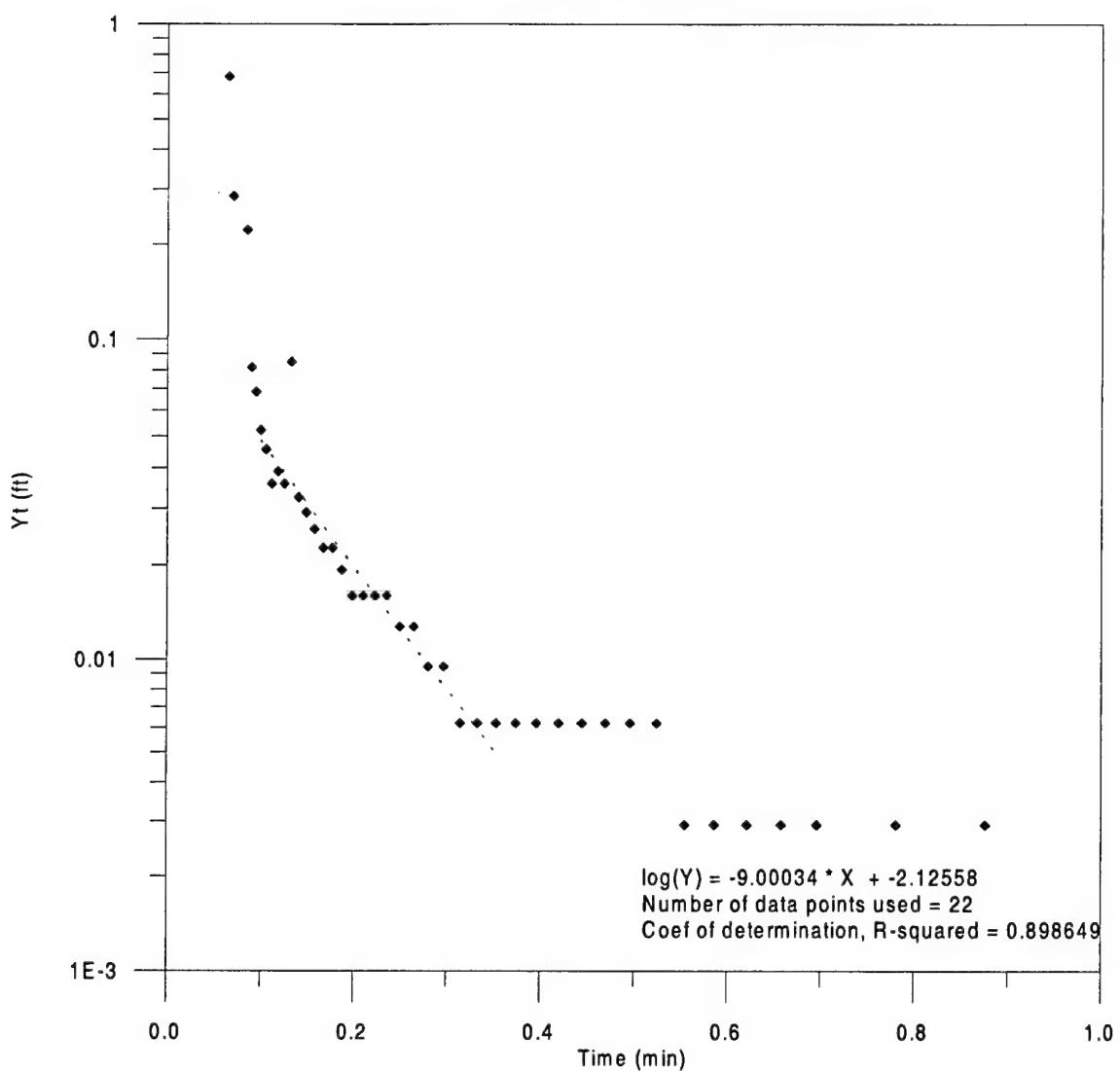
**Post-demonstration Slug Test Results: Well BAT-6I.**

### Well BAT-6S



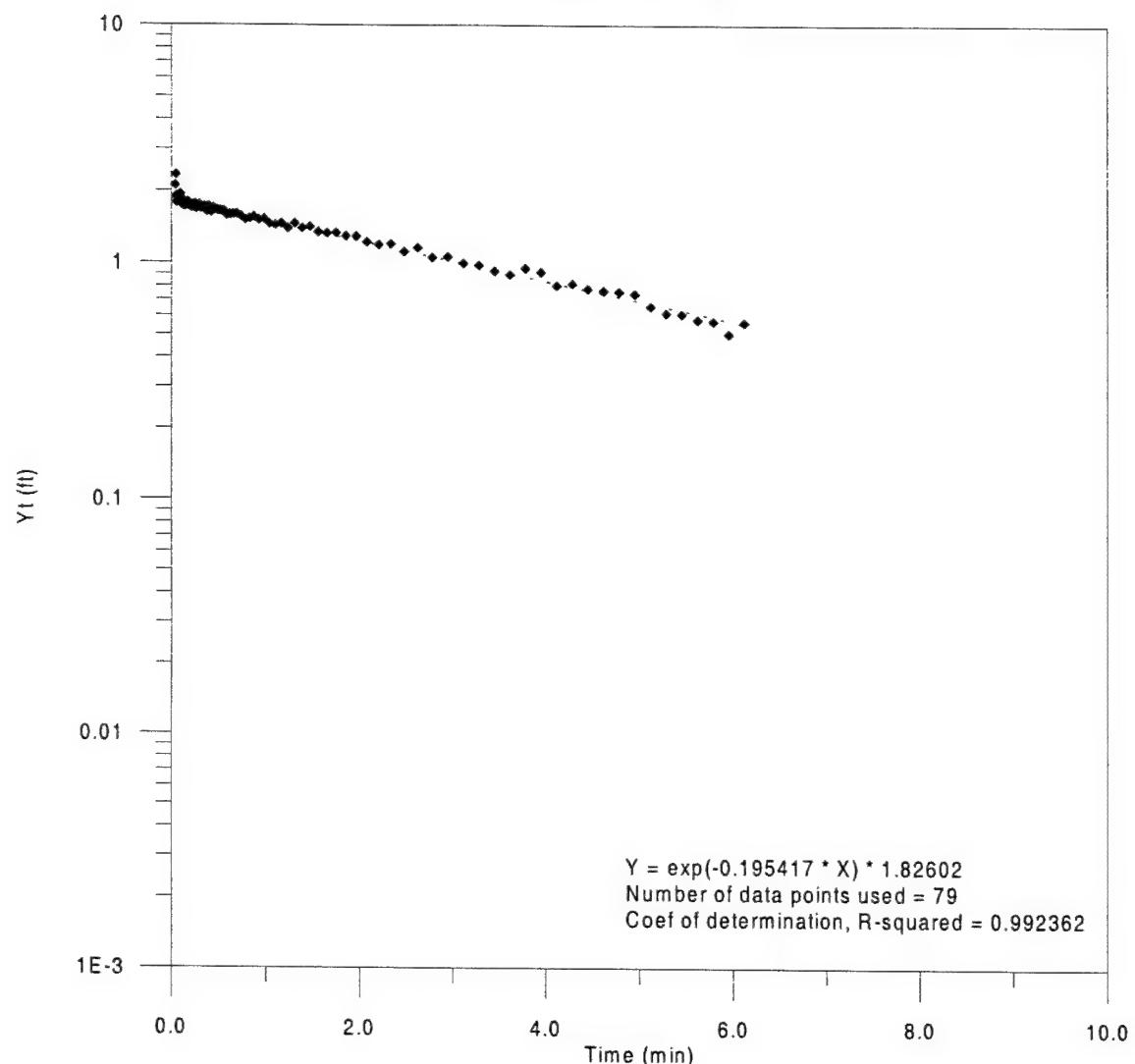
**Post-demonstration Slug Test Results: Well BAT-6S.**

### Well BAT-3D



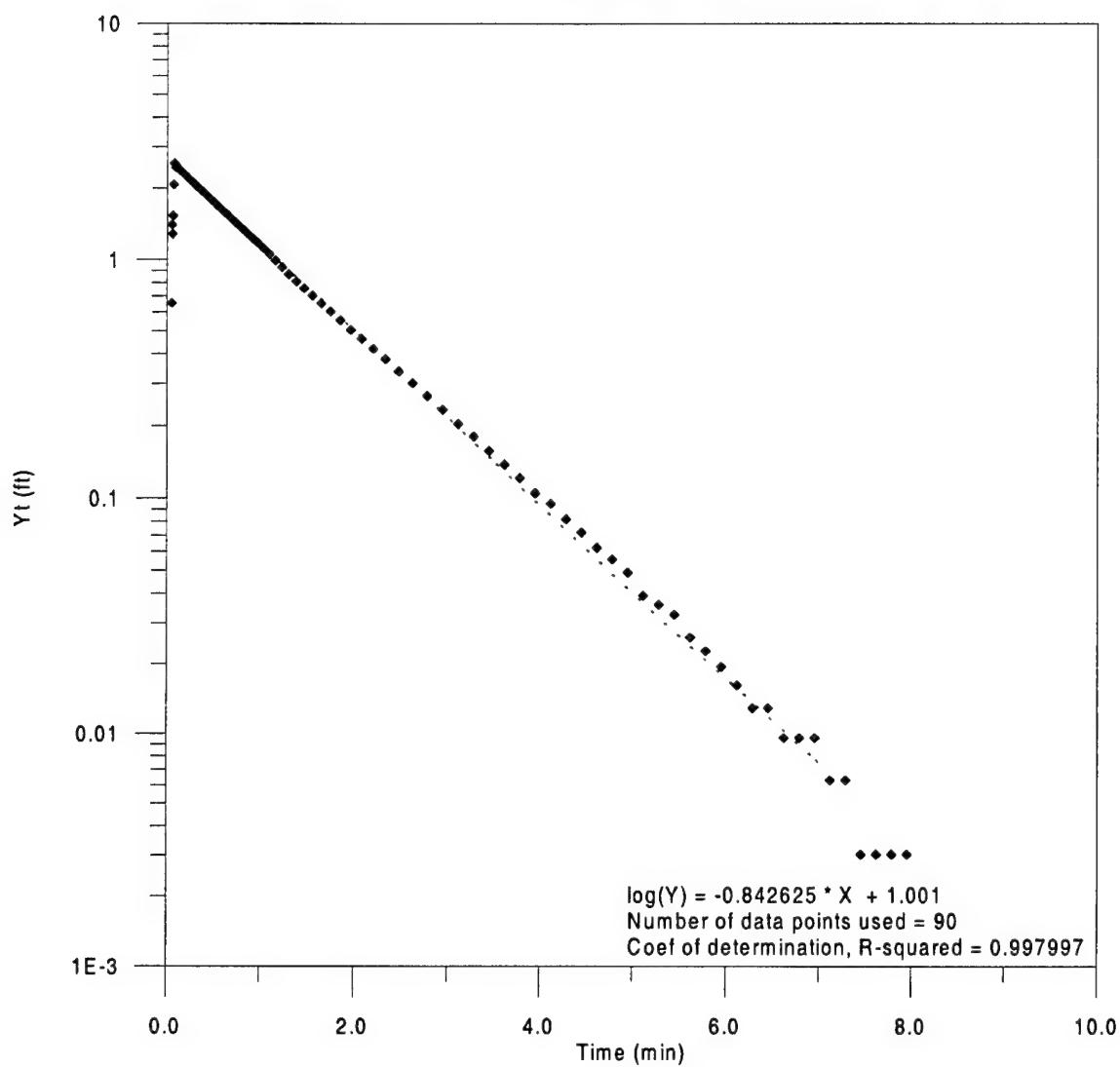
Extended Monitoring Slug Test Results: Well BAT-3D.

### Well BAT-3I



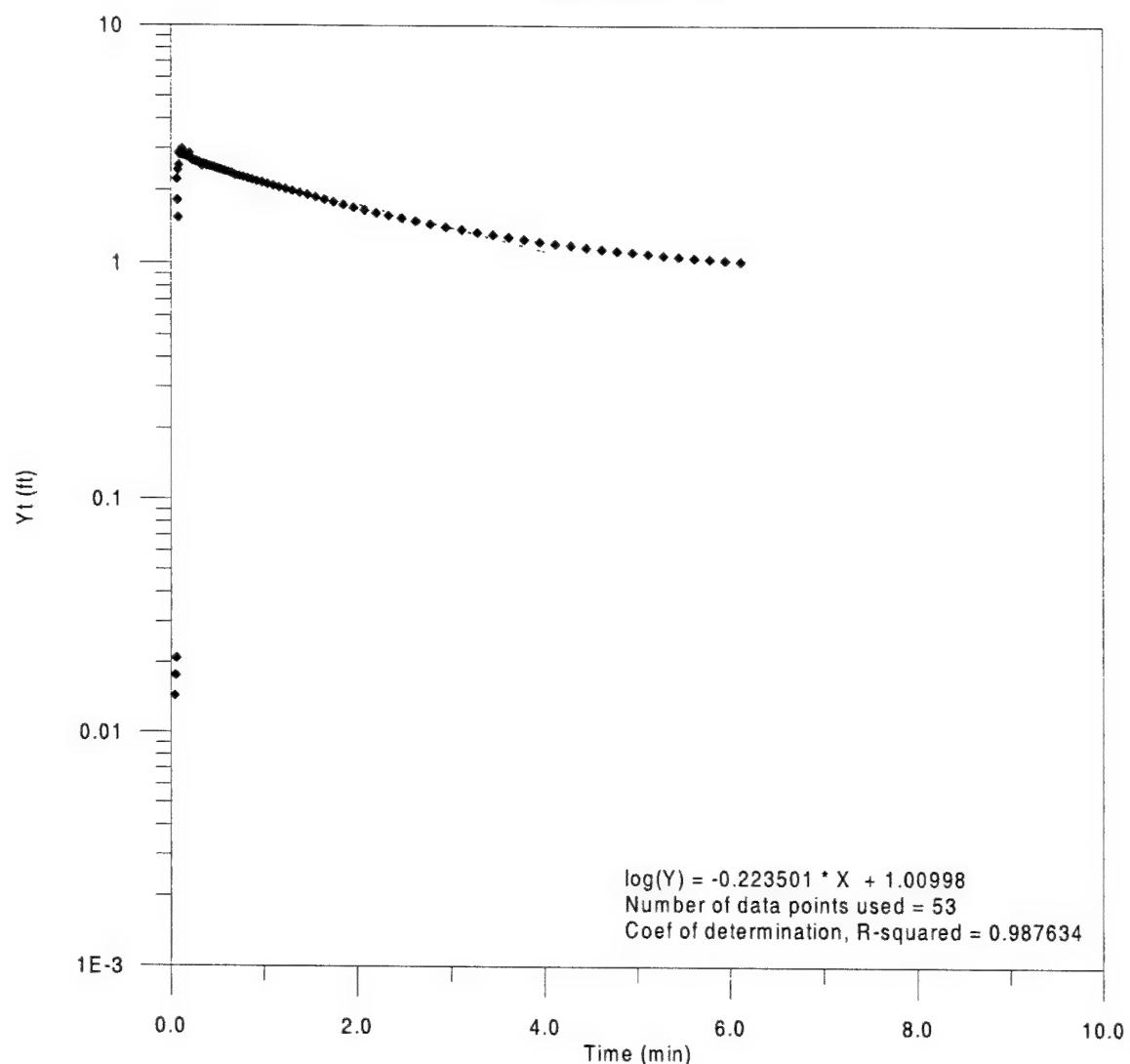
Extended Monitoring Slug Test Results: Well BAT-3I.

### Well BAT-5I



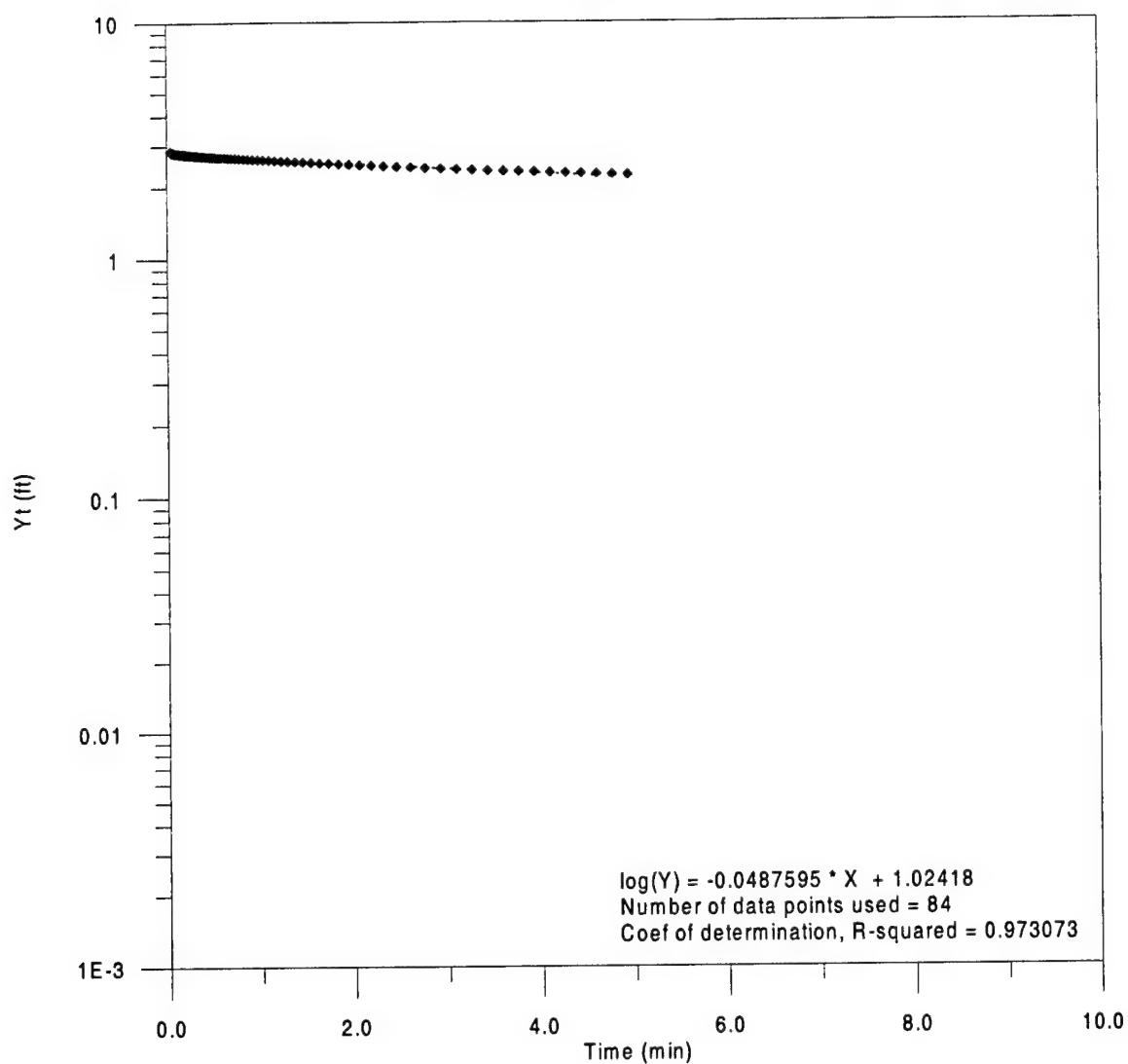
**Extended Monitoring Slug Test Results: Well BAT-5I.**

### Well BAT-5S



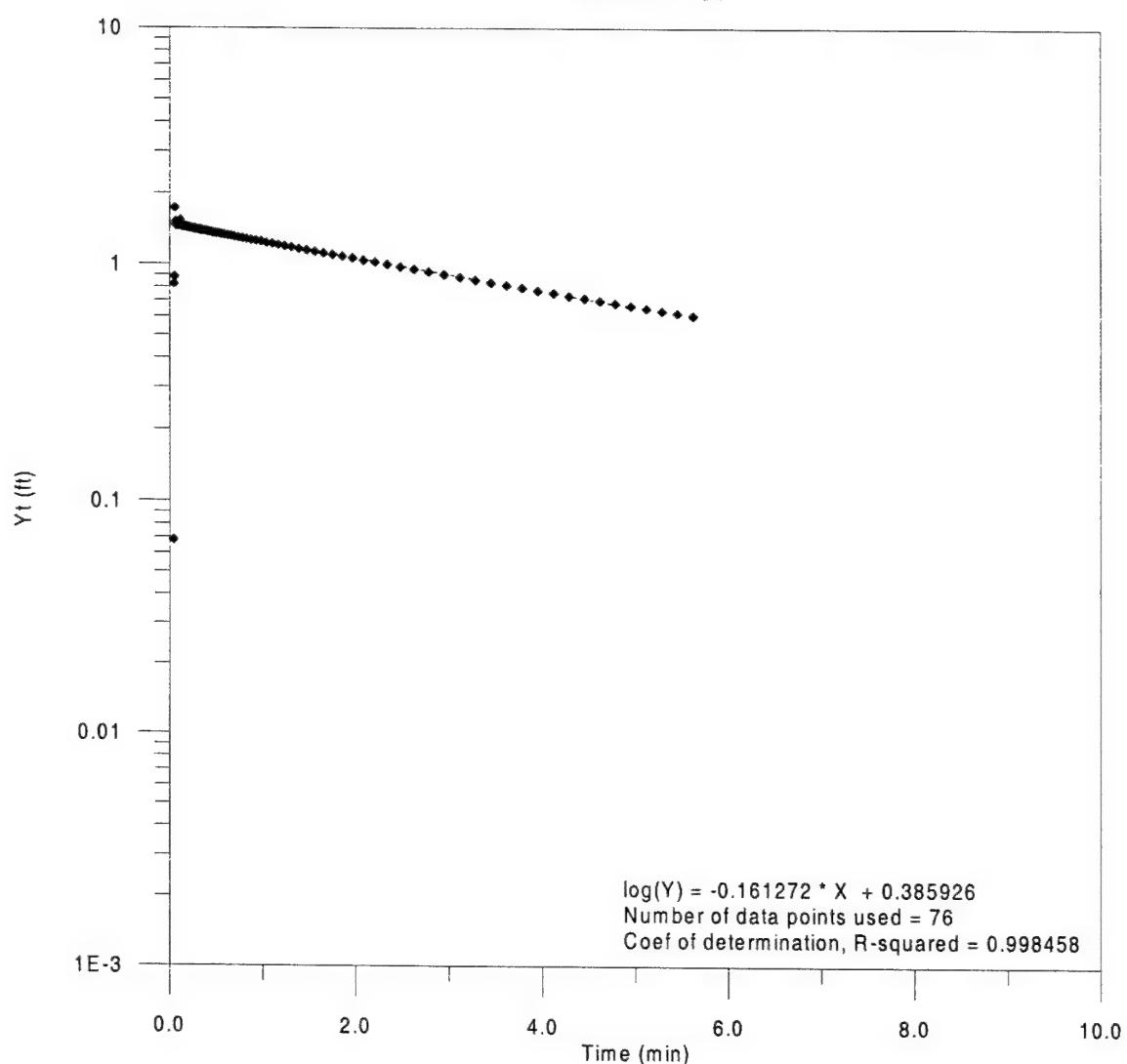
**Extended Monitoring Slug Test Results: Well BAT-5S.**

### Well BAT-6D



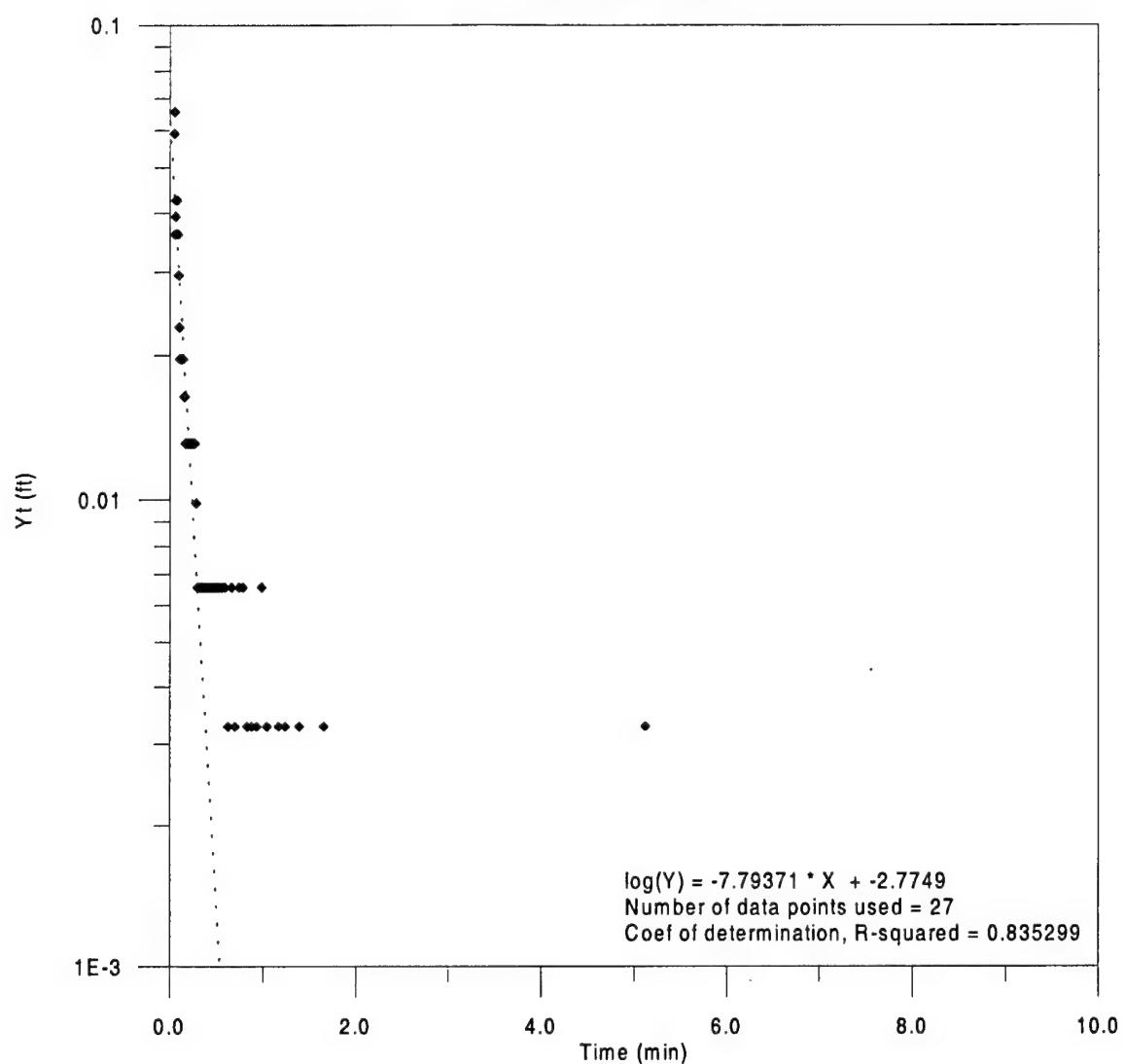
**Extended Monitoring Slug Test Results: Well BAT-6D.**

### Well BAT-6I



**Extended Monitoring Slug Test Results: Well BAT-6I.**

### Well BAT-6S



**Extended Monitoring Slug Test Results: Well BAT-6S.**

## **Appendix C. CVOC Measurements**

C.1 CVOC Measurements in Groundwater

C.2 TCE Analysis of Additional Soil Cores outside the Oxidation Plot

    C.3 Pre-Demo Soil Coring Results

    C.4 Post-Demo Soil Coring Results

Figure C-1. TCE Concentrations and Soil Color Results from the Oxidation Plot Soil Coring

Table C-1. TCE Results of Groundwater Samples

Well ID	Pre-Demo		Week 3-4		Week 5		Week 7-8		Jan 10-14, 2000		Apr 10-14, 2000 <sup>1</sup>		OX Post-Demo	
	Results	Results	% Change in Conc.	Results	% Change in Conc.	Results	% Change in Conc.	Results	% Change in Conc.	Results	% Change in Conc.	Results	% Change in Conc.	Results
<b>Oxidation Plot Wells</b>														
BAT-1S	1,140,000	940,000	-18%	NA	NA	1,010,000	-11%	260,000	-77%	NA	NA	<5	>-99%	
BAT-1I	1,060,000	NA	NA	NA	NA	360,000	-66%	830,000	-22%	NA	NA	360,000	-66%	
BAT-1D	1,130,000	NA	NA	NA	NA	610,000	-46%	<b>675,000</b>	-40%	NA	NA	<b>130,000</b>	-88%	
BAT-2S	1,110,000	14,100	-99%	NA	NA	457	>-99%	<b>84,600</b>	-92%	<5	>-99%	<5	>-99%	
BAT-2S	1,100,000	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
BAT-2S-DUP	1,160,000	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
BAT-2S-DUP	1,100,000	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
BAT-2I	970,000	NA	NA	NA	NA	68,800	-93%	50,000	-95%	<5	>-99%	<b>880</b>	>-99%	
BAT-2I-DUP	NA	NA	NA	NA	NA	60,700	-94%	48,200	-95%	NA	NA	NA	NA	
BAT-2I	880,000	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
BAT-2D	1,160,000	NA	NA	NA	NA	835,000	-28%	<b>675,000</b>	-42%	<b>NS<sup>2</sup></b>	NA	<b>220,000</b>	-81%	
BAT-2D	1,100,000	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
BAT-3S	1,100,000	229,000	-79%	NA	NA	262,000	-76%	79,400	-93%	NA	NA	630,000	-43%	
BAT-3S-DUP	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	600,000	-45%	
BAT-3I	990,000	NA	NA	NA	NA	1,060,000	7%	293,000	-70%	NA	NA	46,000D	-9%	
BAT-3D	962,000	NA	NA	NA	NA	94,200	-90%	<b>223,000</b>	-77%	NA	NA	<5	>-99%	
BAT-5S	298,000	47,800	-84%	NA	NA	1,240,000	316%	47,800	-94%	620,000	108%	410,000	-38%	
BAT-5S	240,000	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
BAT-5I	868,000	NA	NA	NA	NA	985,000	13%	555	>-99%	<5	>-99%	<10	>-99%	
BAT-5I	960,000	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
BAT-5I-DUP	898,000	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
BAT-5I-DUP	760,000	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
BAT-5D	1,140,000	NA	NA	NA	NA	730,000	-36%	915,000	-20%	870,000	-24%	52,000	-95%	
BAT-5D-DUP	NA	NA	NA	NA	NA	725,000	-36%	NA	NA	910,000	-20%	49,000	-96%	
BAT-5D	1,100,000	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
BAT-6S	1,090,000	122	>-99%	NA	NA	1,990	>-99%	432,000	-60%	NA	NA	<b>23,000</b>	-98%	
BAT-6I	998,000	NA	NA	NA	NA	42,500	-96%	<b>44,600</b>	-96%	NA	NA	<b>340</b>	>-99%	
BAT-6D	752,000	NA	NA	NA	NA	164,000	-78%	61,800	-92%	NA	NA	<5	>-99%	
PA-4S	690,000	<2	>-99%	NA	NA	<2	>-99%	7,070	>-99%	NA	NA	<5	>-99%	
PA-4S-DUP	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	<5	>-99%	
PA-4I	1,190,000	NA	NA	NA	NA	274	>-99%	<b>42,500</b>	-96%	NA	NA	<5	>-99%	
PA-4D	1,160,000	NA	NA	NA	NA	1,050,000	-9%	<b>1,120,000</b>	-3%	NA	NA	<5	>-99%	
MP-1A	778,000	6,490	-99%	NA	NA	630,000	-19%	<b>5,420</b>	>-99%	NA	NA	<5	>-99%	
MP-1B	878,000	NA	NA	NA	NA	965,000	10%	<b>775,000</b>	-12%	NA	NA	NA	NA	
MP-1C	812,000	NA	NA	NA	NA	590,000	-27%	540,000	-33%	NA	NA	<b>120,000</b>	-85%	

**Table C-1. TCE Results of Groundwater Samples**

Well ID	'TCE ( $\mu\text{g/L}$ )						OX Post-Demo		
	Pre-Demo	Week 3-4	Week 5	Week 7-8	Jan 10-14, 2000	Apr 10-14, 2000 <sup>1</sup>	% Change in Conc.	Results in Conc.	% Change in Conc.
MP-1D	608,000	NA	NA	NA	603,000	-1%	484,000	-20%	NA
MP-1E	628,000	NA	NA	NA	965,000	54%	372,000	-41%	NA
ML-2	92,500	NA	NA	NA	<2	>-99%	58.2	>-99%	NA
ML-3	61,800	203,000	228%	NA	NA	Dry	NA	NA	NA
ML-4	982,000	1,010,000	3%	NA	545,000	-45%	9,850	-99%	NA
ML-5	750,000	NA	NA	NA	595,000	-21%	240,000	-68%	NA
ML-6	595,000	NA	NA	NA	610,000	3%	273,000	-54%	NA
ML-7	435,000	NA	NA	NA	775,000	78%	350,000	-20%	NA
MP-2A	428,000	5,050	>-99%	NA	NA	<2	>-99%	180	>-99%
MP-2A-2	NA	<2	>-99%	NA	NA	NA	NA	NA	<5
MP-2B	760,000	NA	NA	NA	NA	290	>-99%	Dry	NA
MP-2B-DUP	NA	NA	NA	NA	NA	265	>-99%	NA	NA
MP-2C	695,000	NA	NA	NA	NA	1,21	>-99%	16.5	>-99%
MP-2D	635,000	NA	NA	NA	NA	1,300	>-99%	190,000	-70%
MP-2E	622,000	NA	NA	NA	NA	2,640	>-99%	29,700	-95%
MP-3A	515,000	36.3	>-99%	NA	NA	<2	>-99%	191,000	-63%
MP-3B	800,000	NA	NA	NA	60,000	-93%	49,700	-94%	NA
MP-3C	768,000	NA	NA	NA	8.55	>-99%	247,000	-68%	NA
MP-3D	528,000	NA	NA	NA	NA	127,000	-76%	432,000	-18%
MP-3E	558,000	NA	NA	NA	420,000	-25%	341,000	-39%	NA
MP-4A	745,000	<2	>-99%	NA	NA	<2	>-99%	176	>-99%
MP-4C	810,000	NA	NA	NA	2,980	>-99%	92,200	-89%	NA
MP-4E	830,000	NA	NA	NA	338,000	-59%	710,000	-14%	NA
MP-4E-2	NA	NA	NA	NA	NA	NA	NA	NA	91,000
<b>Oxidation Perimeter Plot Wells</b>									
PA-3S	652,000	950,000	46%	NA	NA	580,000	-11%	85,800	-87%
PA-3S-DUP	NA	NA	NA	NA	NA	NA	NA	NA	<5
PA-3I	1,100,000	1,150,000	5%	NA	NA	600,000	-45%	39,300	-96%
PA-3I-DUP	NA	1,160,000	5%	NA	NA	NA	NA	NA	330J
PA-3D	1,080,000	1,130,000	5%	NA	NA	585,000	-46%	650,000	-40%
PA-3D-DUP	NA	NA	NA	NA	NA	NA	NA	NA	<10
PA-5S	197	84,500	42,793%	NA	NA	9,600	4,773%	750,000	380,611%
PA-5S-2	120	NA	NA	NA	NA	NA	NA	NA	NA
PA-5I	17,200	71,000	313%	NA	NA	114,000	563%	670,000	3,795%
PA-5D	183,000	170,000	-7%	NA	NA	258,000	41%	570,000	211%
PA-5D-2	163,000	NA	NA	NA	NA	NA	NA	NA	66,000

**Table C-1. TCE Results of Groundwater Samples**

Well ID	TCE ( $\mu\text{g/L}$ )						OX Post-Demo								
	Pre-Demo	Week 3-4	Week 5	Week 7-8	Jan 10-14, 2000	Apr 10-14, 2000 <sup>1</sup>	Results	% Change in Conc.	Results	% Change in Conc.	Results	% Change in Conc.	Results	% Change in Conc.	
PA-6S	290	993	242%	NA	10,800	3,624%	68,400	23,486%	33,000	11,279%	24,000	8,176%	NA	NA	
PA-6S-2	131	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
PA-6I	1,010,000	1,050,000	4%	NA	1,280,000	27%	955,000	-5%	880,000	-13%	930,000D	-8%	NA	NA	
PA-6D	988,000	406,000	-59%	NA	NA	665,000	-33%	860,000	-13%	800,000	-19%	610,000	-38%	NA	NA
PA-9S	790,000	1,100,000	39%	NA	NA	1,200,000	52%	1,060,000	34%	220,000	-72%	640,000	-19%	NA	NA
PA-9S-DUP	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	230,000	-71%	NA	NA	
PA-9I	968,000	1,040,000	7%	NA	NA	900,000	-7%	790,000	-18%	530,000	-45%	530,000	-4.5%	NA	NA
PA-9D	288,000	295,000	2%	NA	NA	400,000	39%	580,000	101%	770,000	167%	790,000D	174%	NA	NA
PA-12S	482,000	870,000	80%	NA	NA	1,240,000	157%	1,100,000	128%	990,000	105%	760,000	58%	NA	NA
PA-12I	1,040,000	1,210,000	16%	NA	NA	1,320,000	27%	1,160,000	12%	1,300,000D	25%	1,100,000	6%	NA	NA
PA-12D	565,000	685,000	21%	NA	NA	945,000	67%	965,000	71%	840,000	49%	930,000	65%	NA	NA
<b>SPH Plot Wells</b>															
PA-13S	1,030,000	1,220,000	18%	476,000	-54%	NA	NA	NA	NA	NA	180,000 *	-83%	NA	NA	
PA-13S-DUP	1,100,000	1,240,000	13%	NA	NA	NA	NA	NA	NA	NA	170,000 *	-85%	NA	NA	
PA-13I	1,070,000	1,250,000	17%	268,000	-75%	NA	NA	NA	NA	NA	1,300,000 D*	21%	NA	NA	
PA-13D	892,000	1,160,000	30%	380,000	-57%	NA	NA	NA	NA	NA	3,300 *	>99%	NA	NA	
PA-13D-DUP	730,000	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
PA-14S	935,000	106,000	-89%	556	>-99%	NA	NA	NA	NA	NA	9,400 *	>99%	NA	NA	
PA-14I	960,000	75,500	-92%	NA	NA	NA	NA	NA	NA	NA	46,000 *	-95%	NA	NA	
PA-14D	868,000	482,000	-44%	NA	NA	NA	NA	NA	NA	NA	68,000 *	-92%	NA	NA	
<b>SPH Perimeter Wells</b>															
PA-2S	22,900	1,110	-95%	82,6	>-99%	NA	NA	17,400	-24%	6,400	-72%	19,000	-17%	NA	NA
PA-2I	1,140,000	720,000	-37%	425,000	-63%	NA	NA	1,100,000	-4%	1,800,000D	58%	980,000	-14%	NA	NA
PA-2I-DUP	NA	NA	NA	475,000	-58%	NA	NA	NA	NA	1,400,000D	23%	NA	NA	NA	NA
PA-2D	1,150,000	1,080,000	-6%	1,120,000	-3%	NA	NA	1,250,000	9%	1,300,000D	13%	990,000D	-14%	NA	NA
PA-7S	118,000	92,000	-22%	55,000	-53%	NA	NA	39,600	-66%	64,000	-46%	NA	NA	NA	NA
PA-7I	365,000	486,000	33%	438,000	20%	NA	NA	112,000	-69%	36,000	-90%	NA	NA	NA	NA
PA-7D	309	19,000	6,049%	23,100	7,376%	NA	NA	160,000	51,680%	33,000	10,580%	NA	NA	NA	NA
PA-10S	162,000	299,000	85%	182,000	12%	NA	NA	182,000	12%	760,000D	369%	NA	NA	NA	NA
PA-10I	1,100,000	860,000	-22%	458,000	-58%	NA	NA	280,000	-75%	740,000D	-33%	NA	NA	NA	NA
PA-10I-DUP	NA	NA	NA	451,000	-59%	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PA-10D	1,120,000	180,000	-84%	825,000	-26%	NA	NA	1,060,000	-5%	1,000,000D	-11%	NA	NA	NA	NA
PA-10D-DUP	NA	NA	NA	NA	NA	NA	NA	1,120,000	0%	NA	NA	NA	NA	NA	NA
IW-17S	397	468,000	117,784%	494,000	124,333%	NA	NA	77,500	19,421%	Dry	NA	NA	NA	NA	NA
IW-17I	15,000	17,400	16%	31,000	107%	NA	NA	152,000	913%	680,000	4,433%	NA	NA	NA	NA
IW-17D	154,000	7,410	-95%	1,180	-99%	NA	NA	630J	>-99%	1,600J	>-99%	NA	NA	NA	NA

Table C-1. TCE Results of Groundwater Samples

Well ID	TCE (µg/L)										OX Post-Demo % Change in Conc.	
	Pre-Demo		Week 3-4		Week 5		Week 7-8		Jan 10-14, 2000			
	Results	% Change in Conc.	Results	% Change in Conc.	Results	% Change in Conc.	Results	% Change in Conc.	Results	% Change in Conc.		
PA-15	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
<b>Distant Wells</b>												
PA-1S	984	2,550	159%	9,690	885%	19,400	1,872%	16,200	1,546%	3,700	276%	
PA-11	2,920	4,420	51%	2,310	-21%	288	-90%	140J	-95%	510J	-83%	
PA-II-DUP	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	<2000	
PA-1D	172	845	391%	24.1	-86%	24.6	-86%	2.58	>99%	0.67J	>99%	
PA-8S	5,730	15,300	167%	25,800	350%	115,000	1,907%	79,300	1,284%	740,000	12,814%	
PA-8S-DUP	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
PA-8I	988,000	1,040,000	5%	1,390,000	41%	1,000,000	1%	805,000	-19%	190,000	-81%	
PA-8D	478,000	625,000	31%	635,000	33%	900,000	88%	960,000	101%	1,300,000D	172%	
PA-8D-DUP	NA	555,000	16%	NA	NA	NA	NA	NA	NA	NA	NA	
PA-11S	865,000	800,000	-8%	790,000	-9%	810,000	-6%	1,090,000	26%	970,000	12%	
PA-1II	1,060,000	1,280,000	21%	1,200,000	13%	1,190,000	12%	1,200,000	13%	1,200,000D	13%	
PA-1ID	1,010,000	1,240,000	23%	1,030,000	2%	1,250,000	24%	1,180,000	17%	1,300,000D	29%	

**Notes:**

All units are in µg/L.

NA: Not available.

<: The compound was analyzed but not detected at or above the specified reporting limit.

J: Result was estimated but below the reporting limit.

D: Result was quantified after dilution.

\*: SPH Plot wells sampled in Apr, 2000 may not be representative because most of well screens were appeared to be submerged under sediments.

Red indicates that TCE concentration has increased compared to Pre-demo conditions.

Blue indicates that TCE concentration has decreased compared to Pre-demo conditions.

Purple bold face indicates that water sample was purple when collected.

Table C-2. Other CVOC Results of Groundwater Samples

Well ID	cis -1,2-DCE (µg/L)						trans -1,2-DCE (µg/L)					
	Pre-Demo	Week 3, Week 4	Week 5	Jan 2000	Apr 2000	OX Demo	Pre-Demo	Week 3, Week 4	Week 5	Jan 2000	Apr 2000	OX Post-Demo
<b>Oxidation Plot Wells</b>												
BAT-1S	5,020	4,000I	NA	<10,000	<10,000	NA	<5,000	<10,000	NA	<10,000	<10,000	NA
BAT-1I	5,520	NA	NA	<10,000	<10,000	NA	<17,000	<5,000	NA	<10,000	<10,000	NA
BAT-1D	<5,000	NA	NA	<10,000	<10,000	NA	<7,100	<5,000	NA	<10,000	<10,000	NA
BAT-2S	4,900J	42.8	NA	<20	<2,000	<5	<5,000	<2	NA	<20	<2,000	<5
BAT-2S	NA	NA	NA	NA	NA	NA	<33,000	NA	NA	NA	NA	NA
BAT-2S-DUP	4,800J	NA	NA	NA	NA	NA	<5,000	NA	NA	NA	NA	NA
BAT-2S-DUP	NA	NA	NA	NA	NA	NA	<5,0000	NA	NA	NA	NA	NA
BAT-2I	4,700J	NA	NA	152	<2,000	<5	<5,000	NA	NA	<20	<2,000	<5
BAT-2I	NA	NA	NA	NA	NA	NA	<5,0000	NA	NA	NA	NA	NA
BAT-2I-DUP	NA	NA	NA	150	<2,000	NA	NA	NA	NA	<20	<2,000	NA
BAT-2D	NA	NA	NA	<10,000	360	NA	<10,000	<5,000	NA	<10,000	6	NA
BAT-2D	NA	NA	NA	NA	NA	NA	<5,0000	NA	NA	NA	NA	NA
BAT-3S	4,900J	<10,000	NA	<10,000	8,330	NA	<5,000	<10,000	NA	<10,000	<2,000	NA
BAT-3S-DUP	NA	NA	NA	NA	NA	NA	5,000J	NA	NA	NA	<20	NA
BAT-3I	7,020	NA	NA	<10,000	14,000	NA	<5,000	NA	NA	<10,000	6	NA
BAT-3D	9,180	NA	NA	<2,000	<2,000	NA	<5,000	NA	NA	NA	NA	NA
BAT-5S	12,500	<500	NA	<10,000	<100	<5	<17,000	<5,000	<500	NA	<10,000	<17,000
BAT-5S	9,100J	NA	NA	NA	NA	NA	<10,000	NA	NA	NA	NA	NA
BAT-5I	5,220	NA	NA	<10,000	<2,000	<17,000	<5,000	NA	NA	<10,000	<2,000	<620
BAT-5I	NA	NA	NA	NA	NA	NA	<25,000	NA	NA	NA	NA	NA
BAT-5I-DUP	4,100J	NA	NA	NA	NA	NA	<5,000	NA	NA	NA	<100	<5
BAT-5I-DUP	NA	NA	NA	NA	NA	NA	<5,0000	NA	NA	NA	NA	NA
BAT-5D	NA	NA	NA	<10,000	<10,000	<25,000	<1,700	<5,000	NA	<10,000	<25,000	<1,700
BAT-5D	NA	NA	NA	NA	NA	NA	<5,0000	NA	NA	NA	NA	NA
BAT-5D-DUP	NA	NA	NA	<10,000	NA	<25,000	<1,700	NA	NA	<10,000	NA	<25,000
BAT-6S	3,900J	2.11	NA	<20	1,400I	NA	<5,000	<2	NA	<20	<2,000	NA
BAT-6I	21,300	NA	NA	<10,000	11,300	NA	<5,000	NA	NA	<10,000	<2,000	NA
BAT-6D	44,500	NA	NA	20,200	6,830	NA	<5,000	NA	NA	<10,000	<2,000	NA
PA-4S	5,750	3.46	NA	<2	<2,000	NA	<5,000	<2	NA	<2	<2,000	NA
PA-4S-DUP	NA	NA	NA	NA	NA	NA	<5	NA	NA	NA	NA	<5
PA-4I	4,200J	NA	NA	7.54	<2,000	NA	<5,000	NA	NA	<2	<2,000	NA
PA-4D	NA	NA	<20,000	<10,000	NA	<5	<5,000	NA	NA	<20,000	<10,000	NA
MP-1A	7,180	1.5J	NA	<10,000	<200	NA	<5,000	<2	NA	<10,000	<200	NA
MP-1B	5,000J	NA	<10,000	1,000J	NA	NA	<5,000	NA	NA	<10,000	<2,000	NA
MP-1C	3,200J	NA	<10,000	<10,000	NA	<8,300	<5,000	NA	NA	<10,000	<10,000	<8,300

**Table C-2. Other CVOC Results of Groundwater Samples**

Well ID	cis-1,2-DCE (µg/L)						trans-1,2-DCE (µg/L)						OX-Post-Demo
	Pre-Demo	Week 3-4	Week 5	Week 7	Jan 2000	Apr 2000	OX Demo	Post-Demo	Pre-Demo	Week 3-4	Week 5	Week 7-8	
MP-1D	2,400J	NA	NA <20,000	<10,000	NA	NA	<5,000	NA	NA	<10,000	NA	<10,000	NA <6,200
MP-1E	2,200J	NA	NA <10,000	<10,000	NA	NA	<5,000	NA	NA	<10,000	NA	<10,000	NA <5,000
ML-2	NA	380J	NA <2	<2	NA	NA <5	NA	NA <1,000	NA	<2	NA	<2	NA <5
ML-3	12,800	<10,000	NA Dry	NA Dry	NA	NA	<5,000	<10,000	NA	Dry	NA	Dry	NA Dry
ML-4	4,200J	4,800J	NA <10,000	494	NA	NA	<5,000	<10,000	NA	<10,000	<200	NA	<2,500
ML-5	4,600J	NA	NA <10,000	<10,000	NA	NA	<5,000	NA	NA	<10,000	<10,000	NA	<10,000
ML-6	3,100J	NA	NA <10,000	<10,000	NA	NA	<25,000	<5,000	NA	NA	<10,000	NA	<25,000
ML-7	3,000J	NA	NA <10,000	<10,000	NA	NA	<5,000	NA	NA	<10,000	<10,000	NA	<10,000
MP-2A	7,100	55J	NA <2	<2	NA	NA	<5,000	<100	NA	<2	NA	<2	NA <5
MP-2A-2	NA	1.6J	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
MP-2B	3,100J	NA	NA	NA	NA	NA	<5,000	NA	NA	<20	NA	NA	<5
MP-2B-DUP	NA	NA	NA 13J	NA	NA	NA	NA	NA	NA	<20	NA	NA	NA
MP-2C	<5,000	NA	NA 2.39	<2	NA	NA	<5,000	NA	NA	<2	NA	<2	NA <5
MP-2D	<5,000	NA	NA <40	95.5	NA	NA	<5,000	NA	NA	<40	NA	<50	NA <5
MP-2E	<5,000	NA	NA <40	<1,000	NA	NA	<5,000	NA	NA	<40	<1,000	NA	<20
MP-3A	3,600J	1.7J	NA <2	<2,000	NA	NA	<5,000	<2	NA	<2	<2,000	NA	<2
MP-3B	5,780	NA	NA 84	<2,000	NA	NA	<5,000	NA	NA	<20	<2,000	NA	<5
MP-3C	2,000J	NA	NA 4.87	<2,000	NA	NA	<5,000	NA	NA	<2	<2,000	NA	<5
MP-3D	<5,000	NA	NA <2,000	<10,000	NA	NA <5	<5,000	NA	NA	<2,000	<10,000	NA	<5
MP-3E	<5,000	NA	NA <10,000	<2,000	NA	NA <5	<5,000	NA	NA	<10,000	<2,000	NA	<5
MP-4A	3,900J	6.34	NA <2	<2	NA	NA	<5,000	<2	NA	<2	<2	NA	<5
MP-4C	<5,000	NA	NA <20	<2,000	NA	NA <5	<5,000	NA	NA	<20	<2,000	NA	<5
MP-4E	3,200J	NA	NA <10,000	<10,000	NA	NA <5,000	<5,000	NA	NA	<10,000	<10,000	NA	<1,200
MP-4E-2	NA	NA	NA	NA	NA	NA	<5,000	NA	NA	NA	NA	NA	<5,000
<b>Oxidation Perimeter Wells</b>													
PA-3S	5,250	9,100J	NA <10,000	<2,000	<5		<5,000	<10,000	NA	<10,000	<2,000	<5	<5
PA-3S-DUP	NA	NA	NA	NA	NA	NA	<5	NA	NA	NA	NA	NA	<5
PA-3I	8,750	12,300	NA <10,000	<2,000	2,100		<5,000	<10,000	NA	<10,000	<2,000	<150	<500
PA-3I-DUP	NA	12,200	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PA-3D	<5,000	11,500	NA <10,000	<10,000	<5		<5,000	<10,000	NA	<10,000	<10,000	<5	<10
PA-3D-DUP	NA	NA	NA <10,000	NA	NA	NA	NA	NA	NA	NA	<10,000	NA	NA
PA-5S	2,020	9,800J	NA 6,750	8,330	15,000J		22.6	<10,000	NA	118	<2,000	<33,000	<20,000
PA-5S-2	1,380	NA	NA	NA	NA	NA	11.8	NA	NA	NA	NA	NA	NA
PA-5I	33,500	38,200	NA 54,900	11,300	30,000		<5,000	<10,000	NA	<2,000	<2,000	<10,000	<4,200
PA-5D	68,200	65,500	NA 59,900	13,000	17,000		<5,000	<10,000	NA	<2,000	<2,000	<4,500	<3,100
PA-5D-2	63,600	NA	NA	NA	NA	NA	<2,000	NA	NA	NA	NA	NA	NA

Table C-2. Other CVOC Results of Groundwater Samples

Well ID	cis-1,2-DCE ( $\mu\text{g/L}$ )												trans-1,2-DCE ( $\mu\text{g/L}$ )				OX Post- Demo
	Pre- Demo	Week 4	Week 3	Week 5	Week 7	Jan 2000	Apr 2000	OX Demo	Post Demo	Pre- Demo	Week 4	Week 5	Week 7	Jan 2000	Apr 2000		
PA-6S	774	2,830	NA	14,600	<2,000	1,200				14.7	47.2	NA	299	<2,000	<2,000	<1,000	
PA-6S-2	715	NA	NA	NA	NA	NA	NA	NA	NA	9.8J	NA	NA	NA	NA	NA	NA	
PA-6I	102,000	12,400	NA	24,600	5,570	<33,000				<5,000	<10,000	NA	<10,000	<2,000	<33,000	<25,000	
PA-6D	8,920	90,000	NA	50,500	14,000	<33,000				<5,000	<10,000	NA	<10,000	<2,000	<33,000	<17,000	
PA-9S	24,300	7,800	NA	5,750	37,900	<25,000				<5,000	<10,000	NA	<5,000	<2,000	<25,000	<17,000	
PA-9S-DUP	NA	NA	NA	NA	NA	8,000			NA	NA	NA	NA	NA	NA	NA	NA	
PA-9I	5,420	41,200	NA	64,200	75,000	200,000				<5,000	<10,000	NA	<5,000	<10,000	<25,000	<17,000	
PA-9D	40,200	39,700	NA	38,000	20,400	14,000				<5,000	<10,000	NA	<5,000	<10,000	<25,000	<17,000	
PA-12S	9,380	23,800	NA	4,760	<10,000	<25,000				<5,000	<10,000	NA	<72J	<10,000	<25,000	<50,000	
PA-12I	5,070	6,300	NA	4,160	<10,000	<25,000				<5,000	<10,000	NA	<100	<10,000	<25,000	<50,000	
PA-12D	102,000	61,000	NA	45,000	9,800	<25,000				<5,000	<10,000	NA	<1,000	<10,000	<25,000	<25,000	
<b>SPH Plot Wells</b>																	
PA-13S	4,400	17,400	350,000	NA	NA	NA				NA	<5,000	<10,000	3,000	NA	NA	<5,000	NA
PA-13S-DUP	4,900	16,000	NA	NA	NA	NA				NA	<5,000	<10,000	NA	NA	NA	<5,000	NA
PA-13I	4,900	<10,000	3,900	NA	NA	NA				NA	<5,000	<10,000	NA	NA	NA	6,200	NA
PA-13D	2,200	5,900	3,000	NA	NA	NA				NA	<5,000	<10,000	NA	NA	NA	26J	NA
PA-13D-DUP	<62,000	NA	NA	NA	NA	NA				NA	<42,000	NA	NA	NA	NA	NA	NA
PA-14S	5,880	2,090	19J	NA	NA	NA				NA	<5,000	<200	<20	NA	NA	<560	NA
PA-14I	26,000	349	NA	NA	NA	NA				NA	<5,000	<200	NA	NA	NA	<5,000	NA
PA-14I-DUP	25,500	NA	NA	NA	NA	NA				NA	<5,000	NA	NA	NA	NA	NA	NA
PA-14D	21,900	11,600	NA	NA	NA	NA				NA	<5,000	<10,000	NA	NA	NA	<4,200	NA
PA-14D-DUP	23,200	NA	NA	NA	NA	NA				NA	<5,000	NA	NA	NA	NA	NA	NA
<b>SPH Perimeter Wells</b>																	
PA-2S	3,020	3,520	2,170	NA	32,800	28,000				<500	<20	NA	<1,000	<2,500	<620	NA	
PA-2I	5,480	33,600	2,900	NA	<10,000	7,200				<5,000	<10,000	<5,000	NA	<10,000	<25,000	<25,000	
PA-2I-DUP	NA	NA	3,600	NA	NA	12,000				NA	NA	<5,000	NA	NA	<25,000	NA	
PA-2D	2,700	7,400	3,600	NA	8,500	<25,000				<5,000	<10,000	<5,000	NA	<10,000	<25,000	<25,000	
PA-7S	22,100	19,200	7,430	NA	8,900	NA				<5,000	<10,000	<5,000	NA	<400	<3,300	NA	
PA-7I	160,000	109,000	73,200	NA	21,400	NA				<5,000	<10,000	<5,000	NA	<1,000	290J	NA	
PA-7D	21	38,000	41,800	NA	54,500	NA				NA	2.78	633	<10,000	<10,000	<5,000	NA	
PA-10S	8,880	5,300	1,900	NA	81,000	NA				<5,000	<10,000	<2,000	NA	<10,000	<20,000	NA	
PA-10I	4,700	6,900	4,900	NA	<10,000	NA				<5,000	<10,000	<10,000	NA	<10,000	<20,000	NA	
PA-10I-DUP	NA	NA	<10,000	NA	NA	NA				NA	<10,000	NA	NA	NA	NA	NA	
PA-10D	2,400	<10,000	<10,000	NA	9,800	NA				<5,000	<10,000	<10,000	NA	<10,000	<25,000	NA	
PA-10D-DUP	NA	NA	NA	NA	NA	12,300				NA	NA	NA	NA	NA	NA	NA	
IW-17S	593	15,700	4,640	NA	4,180	Dry				<20	225	140J	NA	<1,000	Dry	NA	

**Table C-2. Other CVOC Results of Groundwater Samples**

Well ID	cis -1,2-DCE (µg/L)						trans -1,2-DCE (µg/L)							
	Pre-Demo	Week 4	Week 5	Week 7-8	Jan 2000	Apr 2000	OX Post Demo	Pre-Demo	Week 4	Week 5	Week 7-8	Jan 2000	Apr 2000	OX Post-Demo
IV-17I	123,000	7,150	7,950	NA	14,600		NA	<5,000	<1,000	<5,000	NA	<1,000	<20,000	NA
IV-17D	39,200	18,100	18,600	NA	70,000		NA	<5,000	150J	251	NA	2,060	1,800J	NA
PA-15	NA	NA	NA	NA	39,300	39,000	NA	NA	NA	NA	NA	<10,000	<5,600	NA
<b>Distant Wells</b>														
PA-1S	1,190	945	5,030	12,800	20,000	29,000		38.4	50J	220	484	714	1,400J	1,100J
PA-II	32,800	22,100	10,800	8,400	43,900	53,000		1,540	1,220	530J	431	1,670	1,500J	1,400J
PA-II-DUP	NA	NA	NA	NA	NA	NA	47,000	NA	NA	NA	NA	NA	NA	1,400J
PA-1D	299	1,100	689	589	1.4J	6.2J		22.9	64J	32.4	21.9	1.2J	0.46J	0.46J
PA-8S	10,000	9,930	12,000	18,200	<2,000	23,000		140J	220	220	352	<2,000	<20,000	<17,000
PA-8S-DUP	NA	NA	NA	18,000	<2,000	NA	NA	NA	NA	NA	368	<2,000	NA	NA
PA-8I	36,800	51,000	64,000	104,000	128,000	220,000		<5,000	<10,000	<1,000	<10,000	<10,000	<17,000	<10,000
PA-8D	36,500	38,600	31,100	20,800	6,600J	11,000J		<5,000	<10,000	<2,000	<10,000	<10,000	<20,000	<25,000
PA-8D-DUP	NA	32,600	NA	NA	NA	NA		<10,000	NA	NA	NA	NA	NA	NA
PA-11S	4,900J	8,000J	5,400J	5,600J	<10,000	<25,000		<5,000	<10,000	<10,000	<10,000	<25,000	<5	<25,000
PA-11I	4,900J	6,900J	5,200J	5,400J	<10,000	5,700J	<25,000	<5,000	<10,000	<10,000	<10,000	<25,000	<25,000	<25,000
PA-11D	6,180	<10,000	6,700J	<10,000	<17,000	<25,000	<5,000	<10,000	<10,000	<10,000	<10,000	<17,000	<25,000	

**Table C-2. Other CVOC Results of Groundwater Samples**

Well ID	Vinyl chloride (µg/L)							OX Post Demo
	Pre-Demo	Week 4	Week 5	Week 7	Jan 2000	Apr 2000		
<b>Oxidation Plot Wells</b>								
BAT-1S	<5,000	<10,000	NA	9,200	<10,000	NA	<10	
BAT-1I	<5,000	NA	NA	<10,000	<10,000	NA	<33,000	
BAT-1D	<5,000	NA	NA	<10,000	<10,000	NA	<14,000	
BAT-2S	<5,000	1.41	NA	<20	<2,000	<10	<10	
BAT-2S	NA	NA	NA	NA	NA	NA	NA	
BAT-2S-DUP	<5,000	NA	NA	NA	NA	NA	NA	
BAT-2S-DUP	NA	NA	NA	NA	NA	NA	NA	
BAT-2I	<5,000	NA	NA	NA	20.7	<2,000	<10	<150
BAT-2I	NA	NA	NA	NA	NA	NA	NA	
BAT-2I-DUP	NA	NA	NA	NA	20.1	<2,000	NA	NA
BAT-2D	<5,000	NA	NA	<10,000	9.79	NA	<20,000	
BAT-2D	NA	NA	NA	NA	NA	NA	NA	
BAT-3S	<5,000	<10,000	NA	<10,000	<2,000	NA	<33,000	
BAT-3S-DUP	NA	NA	NA	NA	NA	NA	<33,000	
BAT-3I	<5,000	NA	NA	<10,000	<2,000	NA	<1,200	
BAT-3D	<5,000	NA	NA	<2,000	<2,000	NA	<10	
BAT-5S	<5,000	<500	NA	<10,000	<100	<10	<33,000	
BAT-5S	NA	NA	NA	NA	NA	NA	NA	
BAT-5I	<5,000	NA	NA	5,100	<2,000	<33,000	<20	
BAT-5I	NA	NA	NA	NA	NA	NA	NA	
BAT-5I-DUP	<5,000	NA	NA	NA	NA	NA	NA	
BAT-5I-DUP	NA	NA	NA	NA	NA	NA	NA	
BAT-5D	<5,000	NA	NA	<0,000	<10,000	<50,000	<3,300	
BAT-5D	NA	NA	NA	NA	NA	NA	NA	
BAT-5D-DUP	NA	NA	<0,000	NA	<50,000	<3,300		
BAT-6S	<5,000	<2	NA	<20	<2,000	NA	<2,000	
BAT-6I	<5,000	NA	NA	<10,000	<2,000	NA	<40	
BAT-6D	<5,000	NA	NA	<10,000	<2,000	NA	<10	
PA-4S	<5,000	<2	NA	<2	<2,000	NA	<10	
PA-4S-DUP	NA	NA	NA	NA	NA	NA	<10	
PA-4I	<5,000	NA	NA	<2	<2,000	NA	<10	
PA-4D	<5,000	NA	NA	<20,000	<10,000	NA	<10	
MP-1A	<5,000	<2	NA	<10,000	<200	NA	<10	
MP-1B	<5,000	NA	NA	<10,000	<2,000	NA	NA	
MP-1C	<5,000	NA	NA	<10,000	<10,000	NA	<17,000	

**Table C-2. Other CVOC Results of Groundwater Samples**

Well ID	Vinyl chloride (µg/L)						OX Post Demo
	Pre-Demo	Week 3-4	Week 5	Week 7-8	Jan 2000	Apr 2000	
MP-1D	<5,000	NA	NA	<20,000	<10,000	NA	<12,000
MP-1E	<5,000	NA	NA	<10,000	<10,000	NA	<10,000
ML-2	NA	<1,000	NA	<2	<2	NA	<10
ML-3	<5,000	<10,000	NA	Dry	Dry	NA	Dry
ML-4	<5,000	<10,000	NA	<10,000	<200	NA	<5,000
ML-5	<5,000	NA	NA	<10,000	<10,000	NA	<20,000
ML-6	<5,000	NA	NA	<10,000	<10,000	NA	<50,000
ML-7	<5,000	NA	NA	<10,000	<10,000	NA	<20,000
MP-2A	<5,000	<100	NA	<2	<2	NA	<10
MP-2A-2	NA	0.8J	NA	NA	NA	NA	NA
MP-2B	<5,000	NA	NA	<20	NA	NA	<10
MP-2B-DUP	NA	NA	NA	<20	NA	NA	NA
MP-2C	<5,000	NA	NA	<2	<2	NA	<10
MP-2D	<5,000	NA	NA	<40	<50	NA	<10
MP-2E	<5,000	NA	NA	<40	<1,000	NA	<40
MP-3A	<5,000	<2	NA	<2	<2,000	NA	<10
MP-3B	<5,000	NA	NA	<20	<2,000	NA	<10
MP-3C	<5,000	NA	NA	<2	<2,000	NA	<10
MP-3D	<5,000	NA	NA	<2,000	<10,000	NA	<10
MP-3E	<5,000	NA	NA	<10,000	<2,000	NA	<10
MP-4A	<5,000	<2	NA	<2	<2	NA	<10
MP-4C	<5,000	NA	NA	<20	<2,000	NA	<10
MP-4E	<5,000	NA	NA	<10,000	<10,000	NA	<2,500
MP-4E-2	NA	NA	NA	NA	NA	NA	<10,000
<b>Oxidation Plot Perimeter Wells</b>							
PA-3S	<5,000	<10,000	NA	<10,000	<2,000	<10	<10
PA-3S-DUP	NA	NA	NA	NA	NA	NA	<10
PA-3I	<5,000	<10,000	NA	<10,000	<2,000	<300	<1,000
PA-3I-DUP	NA	<10,000	NA	NA	NA	NA	NA
PA-3D	<5,000	<10,000	NA	<10,000	<10,000	<10	<20
PA-3D-DUP	NA	NA	NA	<10,000	NA	NA	NA
PA-5S	25.8	<10,000	NA	<100	<2,000	<67,000	<40,000
PA-5S-2	17.2	NA	NA	NA	NA	NA	NA
PA-5I	<5,000	<10,000	NA	<2,000	<2,000	<20,000	<8,300
PA-5D	<5,000	<10,000	NA	<2,000	<2,000	<9,100	<6,200
PA-5D-2	<2,000	NA	NA	NA	NA	NA	NA

Table C-2. Other CVOC Results of Groundwater Samples

Well ID	Vinyl chloride (µg/L)						OX Post Demo
	Pre-Demo	Week 4	Week 5	Week 7-8	Jan 2000	Apr 2000	
PA-6S	<2	<20	NA	<20	<2,000	<4,000	<2,000
PA-6S-2	<10	NA	NA	NA	NA	NA	NA
PA-6I	<5,000	<10,000	NA	<10,000	<2,000	<67,000	<50,000
PA-6D	<5,000	<10,000	NA	<10,000	<2,000	<67,000	<33,000
PA-9S	<5,000	<10,000	NA	<5,000	<2,000	<50,000	<33,000
PA-9S-DUP	NA	NA	NA	NA	NA	<50,000	NA
PA-9I	<5,000	<10,000	NA	<5,000	<10,000	<50,000	<33,000
PA-9D	<5,000	<10,000	NA	<5,000	<10,000	<50,000	<33,000
PA-12S	<5,000	<10,000	NA	<100	<10,000	<50,000	<100,000
PA-12I	<5,000	<10,000	NA	<100	<10,000	<50,000	<100,000
PA-12D	<5,000	<10,000	NA	<1,000	<10,000	<50,000	<50,000
<b>SPH Plot Wells</b>							
PA-13S	<5,000	<10,000	<5,000	NA	NA	<10,000	NA
PA-13S-DUP	<5,000	<10,000	NA	NA	NA	<10,000	NA
PA-13I	<5,000	<10,000	<5,000	NA	NA	<50,000	NA
PA-13D	<5,000	<10,000	<5,000	NA	NA	211	NA
PA-13D	<83,000	NA	NA	NA	NA	NA	NA
PA-14S	<5,000	170I	NA	NA	NA	<1,100	NA
PA-14I	<5,000	100I	NA	NA	NA	<10,000	NA
PA-14I-DUP	<5,000	NA	NA	NA	NA	NA	NA
PA-14D	<5,000	<10,000	NA	NA	NA	<8,300	NA
PA-14D-DUP	<5,000	NA	NA	NA	NA	NA	NA
<b>SPH Perimeter Wells</b>							
PA-2S	<500	<20	<20	NA	<1,000	2,800I	4,100
PA-2I	<5,000	<10,000	<5,000	NA	<10,000	<50,000	<50,000
PA-2I-DUP	NA	NA	<5,000	NA	NA	<50,000	NA
PA-2D	<5,000	<10,000	<5,000	NA	<10,000	<50,000	<50,000
PA-7S	<5,000	<10,000	<5,000	NA	<400	1,200I	NA
PA-7I	<5,000	<10,000	<5,000	NA	<1,000	<3,300	NA
PA-7D	3.3	764	<10,000	NA	<10,000	6,400I	NA
PA-10S	<5,000	<10,000	<2,000	NA	<10,000	2,500I	NA
PA-10I	<5,000	<10,000	<10,000	NA	<10,000	<40,000	NA
PA-10I-DUP	NA	NA	<10,000	NA	NA	NA	NA
PA-10D	<5,000	<10,000	<10,000	NA	<10,000	<50,000	NA
PA-10D-DUP	NA	NA	<10,000	NA	NA	NA	NA
IW-17S	<20	292	<200	NA	<1,000	Dry	NA

**Table C-2. Other CVOC Results of Groundwater Samples**

Well ID	Vinyl chloride (µg/L)						OX Post Demo
	Pre-Demo	Week 3 4	Week 5	Week 7 8	Jan 2000	Apr 2000	
IW-171	<5,000	<1,000	<5,000	NA	<1,000	<40,000	NA
IW-17D	<5,000	428	<200	NA	<1,000	3,800J	NA
PA-15	NA	NA	NA	<10,000	590J	NA	
<b>Distant Wells</b>							
PA-1S	<20	<100	30.3	152	<200	2,400J	2,300J
PA-1I	1,910	1,700	1,260	1,250	6,260	7,200	6,500
PA-1I-DUP	NA	NA	NA	NA	NA	NA	6,300
PA-1D	171	338	332	195	12.1	5.1	4.5
PA-8S	<200	<20	<200	<200	<2,000	<40,000	<33,000
PA-8S-DUP	NA	NA	NA	<200	<2,000	NA	NA
PA-8I	<5,000	<10,000	<1,000	<10,000	<10,000	<33,000	<20,000
PA-8D	<5,000	<10,000	<2,000	<10,000	<10,000	<40,000	<50,000
PA-8D-DUP	NA	<10,000	NA	NA	NA	NA	NA
PA-11S	<5,000	<10,000	<10,000	<10,000	<10,000	<50,000	<10
PA-11I	<5,000	<10,000	<10,000	<10,000	<10,000	<50,000	<50,000
PA-11D	<5,000	<10,000	<10,000	<10,000	<10,000	<33,000	<50,000

**Notes:**

NA: Not available.

<: The compound was analyzed but not detected at or above the specified reporting limit.

J: Result was estimated but below the reporting limit.

D: Result was quantified after dilution.

Yellow indicates that a measurable concentration was obtained for the well.

Red indicates that concentration in this well increased compared to previous sampling.

Blue indicates that concentration in this well decreased compared to previous sampling.

Table C-3. Pre-Demo Results of Soil Samples

Analytical Sample ID	Sample ID	Sample Depth (ft)		TCE						cis-1,2-DCE			trans-1,2-DCE			Vinyl Chloride	
		Top Depth	Bottom Depth	Wet Soil Weight (g)	Dry Soil Weight (g)	Wet Soil MeOH (g)	Dry Soil MeOH (g)	Result in Wet Soil (µg/kg)	Result in Dry Soil (mg/kg)	Reporting Limit Qual	Result in Wet Soil (µg/kg)	Result in Dry Soil (mg/kg)	Reporting Limit Qual	Result in Wet Soil (µg/kg)	Result in Dry Soil (mg/kg)	Result in Wet Soil (µg/kg)	Result in Wet Soil (µg/kg)
SB-13-439	SB-13-2	0	2	195	142	129	330	J	0.4	<	430	ND	ND	ND	ND	ND	
SB-13-440	SB-13-4	2	4	190	201	187	200	J	0.2	<	250	ND	ND	ND	ND	ND	
SB-13-441	SB-13-6	4	6	189	215	194	160	J	0.2	<	280	ND	ND	ND	ND	ND	
SB-13-442	SB-13-8	6	8	189	141	123	300	J	0.4	<	420	ND	ND	ND	ND	ND	
SB-13-443	SB-13-10	8	10	195	198	170	410	J	0.5	<	310	ND	ND	ND	ND	ND	
SB-13-444	SB-13-12	10	12	199	224	173	280	J	0.5	<	250	ND	ND	ND	ND	ND	
SB-13-445	SB-13-14	12	14	191	241	202	300	J	0.4	<	250	ND	ND	ND	ND	ND	
SB-13-446	SB-13-16	14	16	189	221	179	550	J	0.8	<	250	ND	ND	ND	ND	ND	
SB-13-447	SB-13-18	16	18	189	192	160	4,600	J	6.5	400	310	0.6	ND	ND	ND	ND	
SB-13-448	SB-13-20	18	20	191	167	134	15,000	J	720	21.9	BBQ	720	1.3	ND	ND	ND	
SB-13-449	SB-13-22	20	22	189	228	179	66,000	J	2,500	105.9	ND	2,500	ND	ND	ND	ND	
SB-13-450	SB-13-24	22	24	190	231	177	140,000	J	6,200	234.6	J	6,200	ND	ND	ND	ND	
SB-13-451	SB-13-26	24	26	192	248	178	160,000	J	6,200	304.2	J	6,200	ND	ND	ND	ND	
SB-13-452	SB-13-28	26	28	191	243	198	210,000	J	10,000	318.4	J	10,000	ND	ND	ND	ND	
SB-13-453	SB-13-32	26	28	191	243	198	190,000	J	10,000	288.1	J	10,000	ND	ND	ND	ND	
SB-13-453	SB-13-32	30	32	190	300	235	39,000	J	2,500	66.8	J	2,500	56.5	ND	ND	ND	
SB-13-454	SB-13-32B	30	32	197	302	238	39,000	J	2,500	56.5	J	2,500	48.0	ND	ND	ND	
SB-13-454	SB-13-32B	30	32	197	302	238	36,000	J	1,800	60.5	J	1,800	48.8	ND	ND	ND	
SB-13-455	SB-13-34	32	34	190	193	151	18,000	E	250	28.1	E	28,000	59.3	ND	ND	ND	
SB-13-455	SB-13-34	32	34	190	193	151	15,000	D	1,200	23.4	D	30,000	46.8	ND	ND	ND	
SB-13-456	SB-13-36	34	36	191	245	197	4,700	J	2,100	7.3	J	2,100	46.7	ND	ND	ND	
SB-13-457	SB-13-38	36	38	196	198	144	7,500	J	2,600	13.2	J	41,000	53.8	ND	ND	ND	
SB-13-458	SB-13-40	38	40	195	195	154	13,000	J	630	19.9	J	19,000	48.8	ND	ND	ND	
SB-13-459	SB-13-42	40	42	186	215	163	4,000	J	250	6.8	J	7,400	250	ND	ND	ND	
SB-13-460	SB-13-44	42	44	192	275	203	22,000	J	1,000	41.0	J	11,000	20.5	ND	ND	ND	
SB-13-461	SB-13-46	44	46	191	209	160	110,000	J	2,500	180.5	J	4,000	2,500	6.6	ND	ND	
SB-13-462	SB-13-BLANK	NA	0	0	140	J	0	J	250	0.2	J	250	ND	ND	ND	ND	
SB-14-535	SB-14-2	0	2	190	148	138	140	J	440	0.2	J	440	ND	ND	ND	ND	
SB-14-536	SB-14-4	2	4	191	241	231	310	J	260	0.3	J	260	ND	ND	ND	ND	
SB-14-537	SB-14-6	4	6	191	180	174	150	J	350	0.2	J	350	ND	ND	ND	ND	
SB-14-538	SB-14-8	6	8	191	140	126	220	J	480	0.3	J	480	ND	ND	ND	ND	
SB-14-539	SB-14-10	8	10	191	201	171	210	J	290	0.3	J	290	ND	ND	ND	ND	
SB-14-540	SB-14-12	10	12	191	185	151	380	J	400	0.5	J	400	ND	ND	ND	ND	
SB-14-541	SB-14-16	14	16	191	204	158	220	J	320	0.4	180	J	320	0.3	ND	ND	
SB-14-542	SB-14-18	16	18	190	153	124	2,700	J	480	3.8	470	J	480	0.7	ND	ND	
SB-14-543	SB-14-20	18	20	190	222	175	18,000	J	630	28.5	670	J	630	1.1	ND	ND	
SB-14-544	SB-14-22	20	22	189	233	183	71,000	J	3,200	114.3	J	3,200	ND	ND	ND	ND	
SB-14-545	SB-14-24	22	24	191	202	158	150,000	J	4,600	236.0	J	4,600	ND	ND	ND	ND	
SB-14-546	SB-14-26	24	26	192	221	172	140,000	J	4,600	225.8	J	4,600	ND	ND	ND	ND	
SB-14-547	SB-14-28	26	28	191	221	174	2,400,000	J	64,000	3,798.4	J	64,000	ND	ND	ND	ND	
SB-14-548	SB-14-30	28	30	191	186	133	250,000	J	9,100	446.6	J	9,100	ND	ND	ND	ND	
SB-14-549	SB-14-32	30	32	189	221	157	1,200,000	J	35,000	2,261.2	J	35,000	ND	ND	ND	ND	
SB-14-545	SB-14-34	32	34	191	198	154	19,000,000	J	460,000	30,056.1	J	460,000	ND	ND	ND	ND	
SB-14-551	SB-14-36	34	36	190	203	155	5,400,000	J	220,000	8,858.9	J	220,000	ND	ND	ND	ND	
SB-14-552	SB-14-38	36	38	190	186	146	9,800,000	J	270,000	15,113.3	J	270,000	ND	ND	ND	ND	

Table C-3. Pre-Demo Results of Soil Samples (Continued)

Analytical Sample ID	Sample ID	Sample Depth (ft)		Wet Soil		Dry Soil		TCE		cis-1,2-DCE		trans-1,2-DCE		Vinyl Chloride		
		Top Depth	Bottom Depth	MeOH	Weight (g)	Weight (g)	Result in µg/kg	Reporting Qual	Reporting Limit	Result in Dry Soil (mg/kg)	Wet Soil (µg/kg)	Reporting Qual	Reporting Limit	Result in Dry Soil (mg/kg)	Result in Wet Soil (µg/kg)	
SB-14-553	SB-14-40	38	40	191	122	84	490,000		14,000	853.3		<	14,000	ND	ND	
SB-14-554	SB-14-40B	38	40	190	156	112	440,000		11,000	754.8		<	11,000	ND	ND	
SB-14-555	SB-14-14	12	14	191	199	160		1,100		310	1.6		v	310	ND	ND
SB-14-556	SB-14-44	42	44	191	258	184	650,000		18,000	1,264.5		<	18,000	ND	ND	
SB-14-557	SB-14-46	44	46	189	219	164	1,100,000		48,000	1,896.4		<	48,000	ND	ND	
SB-14-558	SB-14-BLANK			184	0	0		<	250	ND		v	250	ND	ND	
SB-15-569	SB-15-2	0	2	191	174	167		<	360	ND		v	360	ND	ND	
SB-15-570	SB-15-4	2	4	190	107	102	180	J	590	0.2		v	590	ND	ND	
SB-15-571	SB-15-6	4	6	192	82	80	430	J	760	0.4		v	760	ND	ND	
SB-15-572	SB-15-8	6	8	190	125	120	410	J	500	0.4		v	500	ND	ND	
SB-15-573	SB-15-10	8	10	191	154	131	580	R	460	0.8		v	460	ND	ND	
SB-15-574	SB-15-12	10	12	190	210	174	1,100	R	300	1.6		v	300	ND	ND	
SB-15-575	SB-15-14	12	14	193	214	177	3,300	R	300	4.8		v	300	ND	ND	
SB-15-576	SB-15-16	14	16	191	208	170	340	R	310	0.5		v	310	ND	ND	
SB-15-577	SB-15-18	16	18	191	251	206	1,400	R	300	2.1		280	J	300	0.4	
SB-15-578	SB-15-20	18	20	190	188	151	860	R	400	1.3		v	400	ND	ND	
SB-15-579	SB-15-22	20	22	190	170	140	20,000		1,400	28.1		v	1,400	ND	ND	
SB-15-580	SB-15-24	22	24	191	210	163	150,000		6,400	240.8		v	6,400	ND	ND	
SB-15-581	SB-15-24B	22	24	190	240	189	140,000		6,400	225.5		v	6,400	ND	ND	
SB-15-582	SB-15-26	24	26	191	203	167	2,100,000		100,000	3,033.8		<	100,000	ND	ND	
SB-15-583	SB-15-28	26	28	193	231	176	7,900,000		220,000	13,323.6		v	220,000	ND	ND	
SB-15-584	SB-15-30	28	30	192	175	136	11,000,000		890,000	17,029.5		v	890,000	ND	ND	
SB-15-585	SB-15-32	30	32	193	190	141	290,000		14,000	490.0		<	14,000	ND	ND	
SB-15-586	SB-15-34	32	34	193	293	216	350,000		23,000	664.2		v	23,000	ND	ND	
SB-15-587	SB-15-38	36	38	193	259	195	10,000,000		660,000	17,886.5		v	660,000	ND	ND	
SB-15-588	SB-15-40	38	40	190	286	226	6,800,000		210,000	11,322.8		v	210,000	ND	ND	
SB-15-589	SB-15-42	40	42	192	216	173	1,800,000		62,000	2,750.7		v	62,000	ND	ND	
SB-15-590	SB-15-44	42	44	193	235	168	2,300,000		58,000	4,334.1		v	58,000	ND	ND	
SB-15-591	SB-15-46	44	46	192	253	194	3,900,000		81,000	6,649.0		<	81,000	ND	ND	
SB-15-592	SB-15-BLANK			192	0	0	780	1	250	1.2		v	250	ND	ND	
SB-16-390	SB-16-2	0	2	190	150	138		<	400	ND		v	400	ND	ND	
SB-16-391	SB-16-4	2	4	192	175	161		<	350	ND		v	350	ND	ND	
SB-16-392	SB-16-6	4	6	190	217	206		<	250	ND		v	250	ND	ND	
SB-16-393	SB-16-8	6	8	193	56	44	200	J	1,100	0.3		v	1,100	ND	ND	
SB-16-394	SB-16-10	8	10	192	124	100	130	J	490	0.2		v	490	ND	ND	
SB-16-395	SB-16-12	10	12	191	185	157	220	J	330	0.3		v	330	ND	ND	
SB-16-396	SB-16-12B	10	12	191	166	140	210	J	360	0.3		v	360	ND	ND	
SB-16-397	SB-16-14	12	14	190	224	177	130	J	250	0.2		v	250	ND	ND	
SB-16-398	SB-16-16	14	16	188	162	135		<	370	ND		v	370	ND	ND	
SB-16-399	SB-16-18	16	18	192	131	162			370	2.6		v	370	0.6	ND	
SB-16-400	SB-16-20	18	20	192	207	160	9,000		500	14.5		v	500	1.4	ND	
SB-16-401	SB-16-22	20	22	191	119	102	15,000		1,000	19.1		250	J	1,000	0.3	
SB-16-402	SB-16-24	24	26	193	210	163	170,000		510	20.3		v	510	ND	ND	
SB-16-26		24					8,300		8,300	27.4		v	8,300	ND	ND	

Table C-3. Pre-Demo Results of Soil Samples (Continued)

Analytical Sample ID	Sample ID	Sample Depth (ft)		TCE						<i>cis</i> -1,2-DCE			<i>trans</i> -1,2-DCE			Vinyl Chloride	
		Top Depth	Bottom Depth	Wet Soil Weight (g)	Dry Soil Weight (g)	MeOH (g)	Wet Soil (µg/kg)	Dry Soil (mg/kg)	Reporting Qual	Result in Wet Soil (µg/kg)	Reporting Qual	Result in Dry Soil (mg/kg)	Reporting Limit	Result in Dry Soil (mg/kg)	Result in Wet Soil (µg/kg)	Result in Wet Soil (µg/kg)	
SB-16-403	SB-16-28	26	28	188	227	166	170,000	5,000	307.9	<	5,000	ND	ND	ND	ND	ND	
SB-16-404	SB-16-30	28	30	189	227	166	220,000	6,200	397.9	<	6,200	ND	ND	ND	ND	ND	
SB-16-405	SB-16-32	30	32	189	197	149	200,000	5,000	331.6	<	5,000	ND	ND	ND	ND	ND	
SB-16-406	SB-16-34	32	34	190	167	129	130,000	3,600	202.0	J	1,600	2.5	ND	ND	ND	ND	
SB-16-407	SB-16-36	34	36	191	196	150	140,000	5,000	227.0	J	4,500	5,000	7.3	ND	ND	ND	
SB-16-408	SB-16-38	36	38	189	240	147	120,000	5,000	292.3	29,000	5,000	70.6	ND	ND	ND	ND	
SB-16-409	SB-16-40	38	40	194	145	109	54,000	1,400	85.2	29,000	1,400	45.7	ND	ND	ND	ND	
SB-16-410	SB-16-42	40	42	192	208	161	140,000	6,200	225.1	J	3,700	6,200	6.0	ND	ND	ND	
SB-16-411	SB-16-44	42	44	192	189	145	170,000	E	3,200	272.4	v	3,200	ND	ND	ND	ND	
SB-16-411	SB-16-44	42	44	192	189	145	180,000	D	6,400	288.4	v	3,200	ND	ND	ND	ND	
SB-16-412	SB-16-46	44	46	195	203	170	35,000	2,500	48.9	J	1,600	2,500	2.2	ND	ND	ND	
SB-16-413	SB-16-24	22	24	189	197	152	110,000	6,200	176.5	v	6,200	ND	ND	ND	ND	ND	
SB-16-414	SB-16-BLANK MeOH Blank Sample	NA	0	0	0	<	250	ND	v	250	ND	v	250	ND	ND	ND	
SB-17-365	SB-17-2	0	2	187	101	94	120	J	580	0.1	v	580	ND	ND	ND	ND	
SB-17-366	SB-17-4	2	4	188	153	143	v	390	ND	v	390	ND	ND	ND	ND	ND	
SB-17-367	SB-17-6	4	6	186	180	167	350	v	330	0.4	v	330	ND	ND	ND	ND	
SB-17-368	SB-17-8	6	8	186	127	107	v	460	ND	v	460	ND	ND	ND	ND	ND	
SB-17-369	SB-17-10	8	10	193	176	148	v	350	ND	v	350	ND	ND	ND	ND	ND	
SB-17-370	SB-17-12	10	12	189	139	115	v	430	ND	v	430	ND	ND	ND	ND	ND	
SB-17-371	SB-17-14	12	14	188	220	183	250	v	250	0.4	v	250	ND	ND	ND	ND	
SB-17-372	SB-17-16	14	16	193	190	149	780	v	320	1.2	v	320	ND	ND	ND	ND	
SB-17-373	SB-17-18	16	18	188	164	145	330	J	360	0.4	v	360	ND	ND	ND	ND	
SB-17-374	SB-17-20	18	20	189	192	150	9,000	500	14.1	v	500	ND	ND	ND	ND	ND	
SB-17-375	SB-17-22	20	22	188	182	140	29,000	1,300	46.1	J	730	1,300	1.2	ND	ND	ND	
SB-17-376	SB-17-24	22	24	188	221	185	3,100,000	170,000	4,412.4	v	170,000	ND	ND	ND	ND	ND	
SB-17-377	SB-17-26	24	26	192	195	154	140,000	5,000	215.1	v	5,000	ND	ND	ND	ND	ND	
SB-17-378	SB-17-28	26	28	190	137	106	140,000	5,500	ND	v	5,500	ND	ND	ND	ND	ND	
SB-17-379	SB-17-30	28	30	191	208	151	190,000	6,200	339.8	v	6,200	ND	ND	ND	ND	ND	
SB-17-380	SB-17-32	30	32	192	171	124	210,000	7,100	360.5	v	7,100	ND	ND	ND	ND	ND	
SB-17-381	SB-17-34	32	34	192	119	97	140,000	5,100	191.4	v	5,100	ND	ND	ND	ND	ND	
SB-17-382	SB-17-34B	32	34	192	125	98	140,000	4,900	203.7	v	4,900	ND	ND	ND	ND	ND	
SB-17-383	SB-17-36	34	36	193	238	184	130,000	5,000	215.2	v	5,000	ND	ND	ND	ND	ND	
SB-17-384	SB-17-38	36	38	188	145	112	170,000	5,900	289.7	v	5,900	ND	ND	ND	ND	ND	
SB-17-385	SB-17-40	38	40	190	191	141	110,000	4,500	188.2	J	2,400	4,500	4.1	ND	ND	ND	
SB-17-386	SB-17-42	40	42	186	218	173	100,000	3,600	186.5	v	3,600	ND	ND	ND	ND	ND	
SB-17-387	SB-17-44	42	44	193	202	157	87,000	2,500	138.0	J	1,400	2,500	2.2	ND	ND	ND	
SB-17-388	SB-17-46	44	46	185	168	126	150,000	5,800	245.4	v	5,800	ND	ND	ND	ND	ND	
SB-17-389	SB-17-BLANK MeOH Blank Sample	NA	0	0	130	J	1	250	0.2	v	250	ND	ND	ND	ND	ND	
SB-18-293	SB-18-2	2	192	131	125	340	J	460	0.4	v	460	ND	ND	ND	ND	ND	
SB-18-294	SB-18-4	2	4	189	178	168	190	J	340	0.2	230	340	0.3	ND	ND	ND	
SB-18-295	SB-18-6	4	6	188	187	175	270	J	320	0.3	220	320	0.3	ND	ND	ND	
SB-18-296	SB-18-8	6	8	190	71	63	5,700	R	850	6.7	v	850	ND	ND	ND	ND	
SB-18-297	SB-18-10	8	10	188	147	121	210	J	400	0.3	v	400	ND	ND	ND	ND	
SB-18-298	SB-18-12	10	12	194	186	154	360	R	330	0.5	v	330	ND	ND	ND	ND	
SB-18-299	SB-18-14	12	14	191	182	146	290	J	330	0.4	v	330	ND	ND	ND	ND	

Table C-3. Pre-Demo Results of Soil Samples (Continued)

Analytical Sample ID	Sample ID	Sample Depth (ft)			Wet Soil			Dry Soil			TCE			cis-1,2-DCE			trans -1,2-DCE			Vinyl Chloride		
		Top Depth	Bottom Depth	MeOH (g)	Weight (g)	Wet Soil ( $\mu\text{g}/\text{kg}$ )	Qual	Reporting Limit	Dry Soil ( $\text{mg}/\text{kg}$ )	Wet Soil ( $\mu\text{g}/\text{kg}$ )	Qual	Reporting Limit	Dry Soil ( $\text{mg}/\text{kg}$ )	Wet Soil ( $\mu\text{g}/\text{kg}$ )	Qual	Reporting Limit	Dry Soil ( $\text{mg}/\text{kg}$ )	Wet Soil ( $\mu\text{g}/\text{kg}$ )	Qual	Reporting Limit	Dry Soil ( $\text{mg}/\text{kg}$ )	
SB-18-300	SB-18-16	14	16	189	145	113	140 J	410	0.2	160 J	410	0.2	160 J	410	0.2	160 J	410	0.2	160 J	410	0.2	ND
SB-18-301	SB-18-18	16	18	189	149	4,100	R	250	5.9	460	250	0.7	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
SB-18-302	SB-18-20	18	20	190	176	142	24,000	R	1,400	35.1	560	J	1,400	0.8	ND	ND	ND	ND	ND	ND	ND	ND
SB-18-303	SB-18-22	20	22	189	107	80	72,000	R	4,000	110.1	v	v	4,000	ND	ND	ND	ND	ND	ND	ND	ND	ND
SB-18-304	SB-18-22B	20	22	190	105	87	45,000	R	2,900	59.5	v	v	2,900	ND	ND	ND	ND	ND	ND	ND	ND	ND
SB-18-305	SB-18-24	22	24	185	213	178	2,600	000	72,000	3,699.8	v	v	72,000	ND	ND	ND	ND	ND	ND	ND	ND	ND
SB-18-306	SB-18-26	24	26	186	198	151	4,200	000	100,000	6,898.9	v	v	100,000	ND	ND	ND	ND	ND	ND	ND	ND	ND
SB-18-307	SB-18-28	26	28	187	174	136	700,000	E	6,800	1,077.6	v	v	6,800	ND	ND	ND	ND	ND	ND	ND	ND	ND
SB-18-308	SB-18-30	26	28	187	174	136	920,000	D	34,000	1,416.2	v	v	6,800	ND	ND	ND	ND	ND	ND	ND	ND	
SB-18-309	SB-18-32	30	32	191	155	115	360,000	000	10,000	441.9	v	v	10,000	ND	ND	ND	ND	ND	ND	ND	ND	
SB-18-310	SB-18-34	32	34	190	123	96	220,000	000	9,800	321.9	v	v	9,800	ND	ND	ND	ND	ND	ND	ND	ND	
SB-18-311	SB-18-36	34	36	189	206	168	1,200,000	000	29,000	1,767.3	v	v	29,000	ND	ND	ND	ND	ND	ND	ND	ND	
SB-18-312	SB-18-38	36	38	190	175	129	1,900,000	000	57,000	3,201.6	v	v	57,000	ND	ND	ND	ND	ND	ND	ND	ND	
SB-18-313	SB-18-40	38	40	189	149	99	4,400,000	000	130,000	8,374.1	v	v	130,000	ND	ND	ND	ND	ND	ND	ND	ND	
SB-18-314	SB-18-42	40	42	190	143	110	510,000	000	17,000	778.2	v	v	17,000	ND	ND	ND	ND	ND	ND	ND	ND	
SB-18-315	SB-18-44	42	44	190	142	106	210,000	000	11,000	334.6	v	v	11,000	ND	ND	ND	ND	ND	ND	ND	ND	
SB-18-316	SB-18-46	44	46	187	254	199	5,400,000	000	170,000	8,919.7	v	v	170,000	ND	ND	ND	ND	ND	ND	ND	ND	
SB-18-317	SB-18-BLANK	MeOH Blank Sample	NA	0	0	0	5,100	1	250	8.0	v	v	250	ND	ND	ND	ND	ND	ND	ND	ND	ND
SB-19-268	SB-19-2	0	2	189	138.1	135	4,10 J	430	0.4	430	0.4	430	0.4	430	ND	ND	ND	ND	ND	ND	ND	ND
SB-19-269	SB-19-4	2	4	190	106.8	99	470 J	560	0.5	160 J	560	0.2	ND	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-270	SB-19-6	4	6	190	93.7	88	630 J	640	0.7	190 J	640	0.2	ND	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-271	SB-19-8	6	8	190	112.6	93	2,200	000	530	2.9	v	v	530	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-272	SB-19-10	8	10	191	141.2	119	5,600	000	430	7.4	v	v	430	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-273	SB-19-12	10	12	189	223.3	187	420	000	250	0.6	v	v	250	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-274	SB-19-14	12	14	190	174	145	6,300	000	340	8.7	v	v	340	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-275	SB-19-16	14	16	190	180.8	147	300 J	330	0.4	v	v	v	330	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-276	SB-19-18	16	18	190	167.3	135	730	000	360	1.1	220 J	360	0.3	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-277	SB-19-20	18	20	191	208.7	170	1,700	000	250	2.5	430	250	0.6	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-278	SB-19-22	20	22	190	210.9	176	8,200	000	250	111.6	1,000	250	1.4	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-279	SB-19-24	22	24	190	205.5	158	71,000	000	2,500	15.4	v	v	2,500	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-280	SB-19-26	24	26	190	192.2	94	68,000	000	1,800	20.9	v	v	1,800	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-281	SB-19-28	26	28	192	160.6	109	150,000	000	5,400	280.4	v	v	5,400	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-282	SB-19-30	28	30	191	228.8	163	98,000	000	3,600	185.0	v	v	3,600	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-283	SB-19-32B	28	30	188	261.2	200	100,000	000	3,800	173.1	v	v	3,800	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-284	SB-19-32	30	32	191	157.2	123	83,000	000	2,700	125.1	v	v	2,700	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-285	SB-19-34	32	34	190	140.4	114	63,000	000	3,600	88.4	v	v	3,600	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-286	SB-19-36	34	36	189	196.5	153	83,000	000	3,100	131.1	v	v	3,100	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-287	SB-19-38	36	38	189	144.2	113	79,000	000	4,100	117.5	v	v	4,100	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-288	SB-19-40	38	40	191	244	167	97,000	000	4,200	198.9	3,500 J	4,200	7.2	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-289	SB-19-42	40	42	190	151	120	49,000	000	2,300	71.7	2,500	2,300	3.7	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-290	SB-19-44	42	44	192	160	123	75,000	000	3,800	116.4	v	v	3,800	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-291	SB-19-46	44	46	190	213.8	166	95,000	000	3,600	153.1	v	v	3,600	ND	ND	ND	ND	ND	ND	ND	ND	
SB-19-292	SB-19-BLANK	MeOH Blank Sample	NA	0	0	0	150 J,1	250	0.2	v	v	250	ND	ND	ND	ND	ND	ND	ND	ND	ND	
SB-20-318	SB-20-2	0	2	189	106.8	99	4,200	000	560	4.7	v	v	560	ND	ND	ND	ND	ND	ND	ND	ND	

Table C-3. Pre-Demo Results of Soil Samples (Continued)

Analytical Sample ID	Sample ID	Sample Depth (ft)		TCE				cis-1,2-DCE		trans-1,2-DCE		Vinyl Chloride Result in Wet Soil ( $\mu\text{g/kg}$ )
		Top Depth	Bottom Depth	Wet Soil Weight (g)	Dry Soil Weight (g)	Result In MeOH (g)	Wet Soil Qual	Reporting Limit	Dry Soil Qual	Result In Wet Soil ( $\mu\text{g/kg}$ )	Reporting Limit	
SB-20-319	SB-20-4	2	4	193	83	77	880 H	730	1.0	730	ND	ND
SB-20-320	SB-20-6	4	6	186	142.2	131	6,800	410	7.8	410	ND	ND
SB-20-321	SB-20-8	6	8	189	104	87	120 J	570	0.2	570	ND	ND
SB-20-322	SB-20-10	8	10	192	94	81	<	640	ND	640	ND	ND
SB-20-323	SB-20-12	10	12	192	173	147	<	350	ND	350	ND	ND
SB-20-324	SB-20-14	12	14	190	164	137	<	370	ND	370	ND	ND
SB-20-325	SB-20-16	14	16	193	156	128	190 J	390	0.3	390	ND	ND
SB-20-326	SB-20-18	16	18	194	145	120	1,300 R	420	1.8	520	420	0.7
SB-20-327	SB-20-20	18	20	189	94	74	8,100	640	11.4	170 J	640	0.2
SB-20-328	SB-20-22	20	22	190	150	121	53,000	2,000	75.7	730 J	2,000	1.0
SB-20-329	SB-20-24	22	24	190	231	180	99,000	3,600	161.2	<	3,600	ND
SB-20-330	SB-20-26	24	26	189	253	199	110,000	5,000	179.8	<	5,000	ND
SB-20-331	SB-20-28B	24	26	191	179	140	120,000	4,800	184.8	<	4,800	ND
SB-20-332	SB-20-28	26	28	191	243	140	200,000	8,300	534.3	<	8,300	ND
SB-20-332	SB-20-28	26	28	191	243	140	170,000	6,200	454.2	<	6,200	ND
SB-20-333	SB-20-30	28	30	187	114	82	160,000	5,200	260.5	<	5,200	ND
SB-20-334	SB-20-32	30	32	187	139	103	130,000	4,200	209.2	<	4,200	ND
SB-20-335	SB-20-34	32	34	186	147	120	140,000	5,700	196.4	<	5,700	ND
SB-20-335	SB-20-34	32	34	186	147	120	120,000	5,000	168.3	<	5,000	ND
SB-20-336	SB-20-36	34	36	191	194	152	110,000	3,600	171.3	<	3,600	ND
SB-20-337	SB-20-38	36	38	186	174	135	120,000	3,400	187.1	<	3,400	ND
SB-20-338	SB-20-40	38	40	190	233	179	92,000	4,200	153.8	<	4,200	ND
SB-20-339	SB-20-44	42	44	189	219	169	150,000	5,000	245.8	<	5,000	ND
SB-20-340	SB-20-46	44	46	189	122	167	15,000,000	490,000	8,349.0	<	490,000	ND
SB-20-341	SB-20-BLANK	NA	0	0	0	6001	250	0.9	<	250	ND	ND
SB-21-245	SB-21-2	0	2	192	86	80	310 J	710	0.3	440 J	710	0.5
SB-21-246	SB-21-4	2	4	187	58	52	600 J	1,000	0.7	610 J	1,000	0.7
SB-21-247	SB-21-6	4	6	191	75	64	200 J	800	0.2	200 J	800	0.2
SB-21-248	SB-21-8	6	8	189	129	95.2	<	460	ND	180 J	460	0.3
SB-21-249	SB-21-10	8	10	190	123	109	220 J	490	0.3	170 J	490	0.4
SB-21-250	SB-21-12	10	12	193	146	116	290 J	420	0.4	360 J	420	0.5
SB-21-251	SB-21-14	12	14	190	101	85	580 J	590	0.7	260 J	590	0.3
SB-21-247	SB-21-16	14	16	191	154	131	350 J	390	0.5	230 J	390	0.3
SB-21-253	SB-21-18	16	18	189	136	120	900	440	1.1	300 J	440	0.4
SB-21-254	SB-21-20	18	20	193	157.3	125	2,300	390	3.4	170 J	390	0.2
SB-21-255	SB-21-22	20	22	190	159.1	129	36,000	1,900	51.4	<	1,900	ND
SB-21-256	SB-21-24	22	24	188	170.4	134	48,000	2,500	72.9	<	2,500	ND
SB-21-257	SB-21-26	24	26	189	146.1	115	44,000	2,000	65.1	<	2,000	ND
SB-21-258	SB-21-28	26	28	190	192.8	141	130,000	2,500	226.2	<	2,500	ND
SB-21-259	SB-21-32	30	32	189	160	122	120,000	6,200	189.0	<	6,200	ND
SB-21-260	SB-21-34	32	34	187	222.2	182	66,000	2,500	97.9	<	2,500	ND
SB-21-261	SB-21-36	34	36	192	260.8	205	7,100,000 E	120,000	1,657.7	<	120,000	ND
SB-21-261	SB-21-36	34	36	192	260.8	205	4,800,000 D	250,000	7,881.2	<	250,000	ND
SB-21-262	SB-21-38	36	38	194	184.3	148	5,000,000	170,000	7,391.4	<	170,000	ND
SB-21-263	SB-21-40	38	40	193	264.3	NA	4,700,000 1	500,000	5,000,000	<	500,000	ND
SB-21-264	SB-21-42	40	42	188	120.6	95	4,100,000	98,000	5,913.6	<	98,000	ND

Table C-3. Pre-Demo Results of Soil Samples (Continued)

Analytical Sample ID	Sample ID	Sample Depth (ft)		Wet Soil		Dry Soil		TCE		cis-1,2-DCE		trans-1,2-DCE		Vinyl Chloride	
		Top Depth	Bottom Depth	MeOH (g)	Weight (g)	Wet Soil (µg/kg)	Dry Soil (µg/kg)	Reporting Limit Qual	Dry Soil (mg/kg)	Wet Soil (µg/kg)	Reporting Limit Qual	Dry Soil (mg/kg)	Wet Soil (µg/kg)	Reporting Limit Qual	Dry Soil (mg/kg)
SB-21-265	SB-21-42B	40	42	190	178.7	140	5,800,000	220,000	8,911.2	v	220,000	ND	ND	ND	ND
SB-21-266	SB-21-44	42	44	192	210.7	154	5,900,000	170,000	10,456.1	v	170,000	ND	ND	ND	ND
SB-21-267	SB-21-BLANK	MeOH Blank Sample	NA	0	0	v	250	ND	v	250	ND	ND	ND	ND	ND
SB-22-011	SB-22-2	0	2	191	168.2	161.2	2,700	250	2.9	v	250	ND	ND	ND	ND
SB-22-012	SB-22-4	2	4	193	284.2	275.3	v	250	ND	v	250	ND	ND	ND	ND
SB-22-013	SB-22-6	4	6	191	252.2	229.8	1,600	250	2.0	v	250	ND	ND	ND	ND
SB-22-014	SB-22-8	6	8	192	162.2	142.2	v	250	ND	v	250	ND	ND	ND	ND
SB-22-015	SB-22-10	8	10	193	130.2	100.4	v	250	ND	v	250	ND	ND	ND	ND
SB-22-016	SB-22-12	10	12	191	184.2	151.6	v	250	ND	v	250	ND	ND	ND	ND
SB-22-017	SB-22-14	12	14	190	184.2	151.6	v	250	ND	v	250	ND	ND	ND	ND
SB-22-018	SB-22-16	14	16	193	224.2	186.9	1,800	250	2.6	v	250	ND	ND	ND	ND
SB-22-019	SB-22-16B	14	16	192	292.2	236.9	1,300	250	2.1	v	250	ND	ND	ND	ND
SB-22-020	SB-22-18	16	18	191	184.2	155	420	250	0.6	v	250	ND	ND	ND	ND
SB-22-021	SB-22-20	18	20	193	176.2	138.9	4,400	500	6.7	v	250	ND	ND	ND	ND
SB-22-022	SB-22-22	20	22	192	162.2	131.9	8,800	1,000	12.5	v	250	ND	ND	ND	ND
SB-22-023	SB-22-24	22	24	189	144.2	120.2	37,000	2,000	50.0	v	250	ND	ND	ND	ND
SB-22-024	SB-22-26	24	26	193	186.2	155.5	40,000	5,000	55.5	v	250	ND	ND	ND	ND
SB-22-025	SB-22-28	26	28	190	186.6	143.1	97,000	12,000	155.4	v	250	ND	ND	ND	ND
SB-22-026	SB-22-30	28	30	190	233.5	177.1	84,000	12,000	143.6	v	250	ND	ND	ND	ND
SB-22-027	SB-22-32	30	32	192	239.1	197.2	39,000	5,000	57.6	v	250	ND	ND	ND	ND
SB-22-028	SB-22-34	32	34	188	193.2	168.5	39,000	2,500	50.6	v	250	ND	ND	ND	ND
SB-22-029	SB-22-36	34	36	191	254.2	193.6	49,000	E	3,100	84.8	11,000	3,100	19.0	ND	ND
SB-22-030	SB-22-38	36	38	191	254.2	193.6	52,000	D	5,000	69.9	v	250	ND	ND	ND
SB-22-031	SB-22-40	38	40	188	202	168.5	39,000	12,000	165.8	v	250	ND	ND	ND	ND
SB-22-032	SB-22-42	38	40	188	252.2	202	73,000	D	10,000	115.5	v	250	ND	ND	ND
SB-22-032	SB-22-42	40	42	190	154.2	130	69,000	E	2,500	92.3	v	250	ND	ND	ND
SB-22-033	SB-22-44	42	44	190	219.2	227	78,000	D	5,000	104.3	v	250	ND	ND	ND
SB-22-033	SB-22-44	42	44	190	279.2	227	37,000	E	2,500	58.0	2,900	2,500	4.5	ND	ND
SB-22-035	SB-22-46	44	46	188	211.2	161	13,000	0	1,000	v	250	ND	ND	ND	ND
SB-22-055	SB-22-BLANK	MeOH Blank Sample	NA	0	v	v	v	250	ND	v	250	ND	ND	ND	ND
SB-23-001	SB-23-2	0	2	191	256.2	243.7	v	v	250	ND	v	250	ND	ND	ND
SB-23-002	SB-23-4	2	4	191	270.2	263	1,700	v	250	1.8	v	250	ND	ND	ND
SB-23-003	SB-23-6	4	6	191	280.2	233	1,600	v	250	1.9	v	250	ND	ND	ND
SB-23-056	SB-23-8	6	8	193	136	114.8	v	450	ND	v	450	ND	ND	ND	ND
SB-23-057	SB-23-10	8	10	191	126	101	v	480	ND	v	480	ND	ND	ND	ND
SB-23-058	SB-23-12	10	12	193	196	161.8	v	250	ND	v	250	ND	ND	ND	ND
SB-23-059	SB-23-14	12	14	192	156	125.8	210	J	390	0.3	v	390	ND	ND	ND
SB-23-060	SB-23-16	14	16	190	163	136.8	v	370	ND	v	370	ND	ND	ND	ND
SB-23-061	SB-23-18	16	18	192	123	100	540	v	490	0.7	190	490	0.3	ND	ND
SB-23-062	SB-23-20	18	20	192	214	179.2	940	v	250	1.3	560	250	0.8	ND	ND
SB-23-063	SB-23-22	20	22	190	199	160.2	40,000	v	1,200	59.8	1,200	1,200	1.8	ND	ND
SB-23-064	SB-23-24	22	24	186	162	123.9	100,000	v	3,600	157.5	v	3,600	ND	ND	ND
SB-23-065	SB-23-26	24	26	193	147	111	110,000	v	4,100	172.8	v	4,100	ND	ND	ND

Table C-3. Pre-Demo Results of Soil Samples (Continued)

Analytical Sample ID	Sample ID	Sample Depth (ft)		TCE				cis -1,2-DCE				trans -1,2-DCE			
		Top Depth	Bottom Depth	Wet Soil Weight (g)	Dry Soil Weight (g)	Wet Soil MeOH (µg/kg)	Dry Soil MeOH (µg/kg)	Reporting Limit (mg/kg)	Reporting Qual	Result in Wet Soil (µg/kg)	Result in Dry Soil (mg/kg)	Reporting Limit (mg/kg)	Result in Wet Soil (µg/kg)	Result in Dry Soil (mg/kg)	Result in Wet Soil (µg/kg)
SB-23-066	SB-23-28	26	28	193	143	102	160,000	5,700	<	272.0	<	5,700	ND	ND	ND
SB-23-067	SB-23-30	28	30	193	215	153.9	180,000	5,000	381.1	<	5,000	ND	ND	ND	ND
SB-23-068	SB-23-32	30	32	192	177	123.9	170,000	6,800	310.0	<	6,800	ND	ND	ND	ND
SB-23-069	SB-23-34	32	34	192	185	146.6	97,000	3,300	146.9	<	3,300	ND	ND	ND	ND
SB-23-070	SB-23-34B	32	34	193	124	9.9	87,000	3,300	125.1	<	3,300	ND	ND	ND	ND
SB-23-071	SB-23-36	34	36	188	167	132	68,000	2,000	102.0	<	2,000	ND	ND	ND	ND
SB-23-072	SB-23-38	36	38	192	142	NA	170,000	1	5,700	267.6	<	5,700	ND	ND	ND
SB-23-073	SB-23-40	38	40	193	131	92	130,000	6,200	225.5	<	6,200	ND	ND	ND	ND
SB-23-074	SB-23-42	40	42	189	174	132.4	90,000	3,400	144.5	<	3,400	ND	ND	ND	ND
SB-23-075	SB-23-45	43	45	192	189	NA	84,000	E.1	320	132.2	<	320	ND	ND	ND
SB-23-075	SB-23-45	43	45	192	189	NA	95,000	D.1	6,400	149.5	<	320	ND	ND	ND
SB-23-076	SB-23-BLANK	MeOH Blank Sample	NA	0	0	750	1	250	1.8	<	250	ND	ND	ND	ND
SB-24-149	SB-24-2	0	2	192	120	112	440	250	0.5	<	250	ND	ND	ND	ND
SB-24-150	SB-24-4	2	4	191	120	113	250	250	0.3	<	250	ND	ND	ND	ND
SB-24-151	SB-24-6	4	6	191	195	175	<	250	ND	<	250	ND	ND	ND	ND
SB-24-152	SB-24-8	6	8	189	59	47	<	250	ND	<	250	ND	ND	ND	ND
SB-24-153	SB-24-10	8	10	190	143	115	6,000	500	8.6	<	500	ND	ND	ND	ND
SB-24-154	SB-24-12	10	12	190	97	80	5,600	250	7.4	<	250	ND	ND	ND	ND
SB-24-155	SB-24-14	12	14	190	187	142	2,600	250	4.2	<	250	ND	ND	ND	ND
SB-24-156	SB-24-16	14	16	193	123	100	3,900	250	5.4	<	250	ND	ND	ND	ND
SB-24-157	SB-24-18	16	18	191	135	110	3,700	250	5.1	260	250	0.4	ND	ND	ND
SB-24-158	SB-24-20	18	20	191	113	86	6,700	500	10.0	<	500	ND	ND	ND	ND
SB-24-159	SB-24-22	20	22	190	205	161	22,000	2,500	34.5	<	2,500	ND	ND	ND	ND
SB-24-160	SB-24-24	22	24	192	137	103	37,000	2,500	57.9	<	2,500	ND	ND	ND	ND
SB-24-161	SB-24-26	24	26	191	250	204	39,000	5,000	59.3	<	5,000	ND	ND	ND	ND
SB-24-162	SB-24-28	26	28	190	159	120	120,000	10,000	191.6	<	10,000	ND	ND	ND	ND
SB-24-163	SB-24-30	28	30	190	216	169	81,000	10,000	137.3	<	10,000	ND	ND	ND	ND
SB-24-164	SB-24-32	30	32	191	171	136	57,000	5,000	84.8	<	5,000	ND	ND	ND	ND
SB-24-165	SB-24-34	32	34	190	132	106	44,000	5,000	62.3	<	5,000	ND	ND	ND	ND
SB-24-166	SB-24-36	34	36	190	194	138	85,000	10,000	154.7	<	10,000	ND	ND	ND	ND
SB-24-167	SB-24-38	36	38	191	114	84	280,000	12,000	439.7	<	12,000	ND	ND	ND	ND
SB-24-168	SB-24-40	38	40	190	261	164	51,000	10,000	101.7	<	10,000	ND	ND	ND	ND
SB-24-169	SB-24-42	40	42	191	166	129	28,000	2,000	43.0	10,000	2,000	15.4	ND	ND	ND
SB-24-170	SB-24-42B	40	42	189	146	115	24,000	2,000	35.5	8,500	2,000	12.6	ND	ND	ND
SB-24-171	SB-24-44	42	44	191	151	115	73,000	5,000	113.9	<	5,000	ND	ND	ND	ND
SB-24-172	SB-24-46	44	46	190	165	126	88,000	10,000	138.9	<	10,000	ND	ND	ND	ND
SB-24-173	SB-24-BLANK	MeOH Blank Sample	NA	0	0	<	250	ND	<	250	ND	ND	ND	ND	ND
SB-25-463	SB-25-2	0	2	189	179	157	250	J	330	0.3	<	330	ND	ND	ND
SB-25-464	SB-25-4	2	4	190	147	131	140	J	410	0.2	<	410	ND	ND	ND
SB-25-465	SB-25-6	4	6	192	187	165	220	J	320	0.3	<	320	ND	ND	ND
SB-25-466	SB-25-8	6	8	193	216	176	240	J	250	0.4	<	250	ND	ND	ND
SB-25-467	SB-25-12	10	12	191	193	163	470	310	0.6	<	310	ND	ND	ND	ND
SB-25-468	SB-25-14	12	14	192	154	350	320	ND	ND	ND	ND	ND	ND	ND	ND
SB-25-469	SB-25-16	14	16	191	168	141	400	360	0.5	<	360	ND	ND	ND	ND
SB-25-470	SB-25-18	16	18	189	172	133	1,000	350	1.6	690	350	1.1	ND	ND	ND

Table C-3. Pre-Demo Results of Soil Samples (Continued)

Analytical Sample ID	Sample ID	Sample Depth (ft)		Wet Soil		Dry Soil		TCE		cis -1,2-DCE		trans -1,2-DCE		Vinyl Chloride	
		Top Depth	Bottom Depth	MeOH (g)	Weight (g)	Wet Soil (µg/kg)	Weight (g)	Reporting Limit	Dry Soil (mg/kg)	Wet Soil (µg/kg)	Reporting Qual	Dry Soil (mg/kg)	Reporting Limit	Dry Soil (mg/kg)	Result in Wet Soil (µg/kg)
SB-25-471	SB-25-18B	16	18	189	173	127	1400	340	2.4	790	-	340	1.3	ND	ND
SB-25-472	SB-25-20	18	20	189	148	112	4,900	400	7.7	1,200	-	400	1.9	ND	ND
SB-25-473	SB-25-22	20	22	192	205	156	9,000	500	14.8	1,600	-	500	2.6	ND	ND
SB-25-474	SB-25-24	22	24	188	161	127	130,000	6,100	194.6	-	v	6,100	ND	ND	ND
SB-25-475	SB-25-26	24	26	192	289	220	140,000	8,300	250.0	-	v	8,300	ND	ND	ND
SB-25-476	SB-25-28	26	28	192	157	112	250,000	7,700	432.6	4,200	J	7,700	7.3	ND	ND
SB-25-477	SB-25-30	28	30	190	231	169	220,000	8,300	398.8	-	v	8,300	ND	ND	ND
SB-25-478	SB-25-32	30	32	193	185	154	14,000	660	19.5	3,300	-	660	4.6	ND	ND
SB-25-479	SB-25-34	32	34	190	198	154	160,000	5,000	253.4	-	v	5,000	ND	ND	ND
SB-25-480	SB-25-36	34	36	192	201	165	66,000	2,100	95.5	1,100	J	2,100	1.6	ND	ND
SB-25-481	SB-25-38	36	38	191	259	183	120,000	5,000	237.4	4,500	J	5,000	8.9	ND	ND
SB-25-482	SB-25-40	38	40	192	204	149	47,000	-	82.8	21,000	-	1,800	37.0	ND	ND
SB-25-483	SB-25-42	40	42	191	224	162	60,000	-	2,500	109.9	-	2,500	49.5	ND	ND
SB-25-484	SB-25-44	42	44	190	232	179	100,000	4,200	165.8	10,000	-	4,200	16.6	ND	ND
SB-25-485	SB-25-46	44	46	192	241	166	130,000	6,200	262.5	-	v	6,200	ND	ND	ND
SB-25-486	SB-25-BLANK MeOH Blank Sample	NA	0	0	<	250	ND	v	250	ND	v	250	ND	ND	ND

Notes:

NA: Not available.

ND: Not detected.

< Result was not detected at or above the stated reporting limit.

1. Dry soil concentration is calculated as 1.57 times of wet soil concentration to account for average moisture content.

D: Result was obtained from the analysis of a dilution.

E: Estimated result. Result concentration exceeds the calibration range.

J: Result was estimated but below the reporting limit.

R: Corresponding rinsate blank contained more than 10 % of this sample result.

Table C-4. Post-Demo VOC Results of Soil Samples

Analytical Sample ID	Preliminary Draft Sample ID	Sample Depth (ft)		Sample Date	Wet Soil Weight (g)	Dry Soil Weight (g)	TCE		cis -1,2-DCE		trans -1,2-DCE		Vinyl chloride Result in Dry Soil (mg/kg)	
		Top Depth	Bottom Depth				Result in MeOH (µg/L)	Dry Soil MeOH (mg/kg)	Result in MeOH (µg/L)	Dry Soil MeOH (mg/kg)	Result in MeOH (µg/L)	Dry Soil MeOH (mg/kg)		
DC-1-1	DC-1-2	0	2	5/24/00	193	121	<250	ND	<250	ND	<250	ND	<500	
DC-1-2	DC-1-4	2	4	5/24/00	196	146	330	0.6	<250	ND	<250	ND	<500	
DC-1-3	DC-1-6	4	6	5/24/00	193	112	330	0.8	<250	ND	<250	ND	<500	
DC-2-4	DC-2-2	0	2	5/24/00	193	118	1,500	3.2	<250	ND	<250	ND	<500	
DC-2-5	DC-2-4	2	4	5/24/00	192	134	1,500	2.7	<250	ND	<250	ND	<500	
DC-2-6	DC-2-6	4	6	5/24/00	165	105	3,100	6.7	260.0	0.6	<250	ND	<500	
DC-3-7	DC-3-2	0	2	5/24/00	193	148	99	530	1.6	420.0	1.2	<250	ND	<500
DC-3-8	DC-3-4	2	4	5/24/00	193	108	650	1.9	<250	ND	<250	ND	<500	
DC-3-9	DC-3-6	4	6	5/24/00	193	107	700	1.6	<250	ND	<250	ND	<500	
SB213-213	SB213-2	0	2	5/24/00	202	151	<250	ND	<250	ND	<250	ND	<500	
SB213-214	SB213-4	2	4	5/24/00	196	141	<250	ND	<250	ND	<250	ND	<500	
SB213-215	SB213-6	4	6	5/24/00	196	141	1,200	2.3	<250	ND	<250	ND	<500	
SB213-216	SB213-8	6	8	5/24/00	200	179	168	<250	ND	<250	ND	<250	ND	
SB213-217	SB213-10	8	10	5/24/00	196	148	119	<250	ND	<250	ND	<250	ND	
SB213-239	SB213-12	10	12	5/24/00	195	187	159	<250	ND	<250	ND	<250	ND	
SB213-240	SB213-14	12	14	5/24/00	196	184	152	<250	ND	<250	ND	<250	ND	
SB213-241	SB213-16	14	16	5/24/00	198	237	185	<250	ND	<250	ND	<250	ND	
SB213-242	SB213-18	16	18	5/24/00	198	288	227	<250	ND	<250	ND	<250	ND	
SB213-243	SB213-20	18	20	5/24/00	193	217	167	<250	ND	<250	ND	<250	ND	
SB213-244	SB213-22	20	22	5/24/00	199	240	192	<250	ND	<250	ND	<250	ND	
SB213-245	SB213-24	22	24	5/24/00	201	297	228	<250	ND	<250	ND	<250	ND	
SB213-246	SB213-26	24	26	5/24/00	199	257	200	<830	ND	15,000	23.2	<830	ND	
SB213-247	SB213-28	26	28	5/24/00	202	242	180	<330	ND	5,900	10.4	<330	ND	
SB213-248	SB213-30	28	30	5/24/00	199	254	185	<250	ND	2,700	4.7	<250	ND	
SB213-249	SB213-30B	28	30	5/24/00	196	340	189	<250	ND	3,900	8.2	<250	ND	
SB213-250	SB213-32	30	32	5/24/00	195	267	99	1,700	7.1	1,700	7.1	<250	ND	
SB213-251	SB213-34	32	34	5/24/00	195	232	186	1,800	2.8	2,000	3.1	<250	ND	
SB213-252	SB213-36	34	36	5/24/00	199	270	209	<250	ND	<250	ND	<250	ND	
SB213-253	SB213-38	36	38	5/24/00	199	253	197	<250	ND	1,400	2.2	<250	ND	
SB213-254	SB213-40	38	40	5/24/00	203	212	154	1,100	2.2	1,800	3.7	<250	ND	
SB213-255	SB213-42	40	42	5/24/00	197	219	178	3,500	5.7	1,700	2.8	<250	ND	
SB213-256	SB213-44	42	44	5/24/00	199	272	194	<250	ND	<250	ND	<250	ND	
SB213-257	SB213-46	44	46	5/24/00	201	203	157	<250	ND	<250	ND	<250	ND	
SB213-258	SB213-46 "S"	44	46	5/24/00	191	271	111	<250	ND	<250	ND	<250	ND	
SB214-306	SB214-2	0	2	5/31/00	192	225	211	<250	ND	<250	ND	<250	ND	

**Table C-4. Post-Demo VOC Results of Soil Samples**

Analytical Sample ID	Preliminary Draft Sample ID	Sample Depth (ft)		Wet Soil Weight (g)	Dry Soil Weight (g)	TCE	cis -1,2-DCE	trans -1,2-DCE	Vinyl chloride		
		Top Depth	Bottom Depth								
SB-214-307	SB214-4	2	4	5/31/00	195	185	<250	ND	<250	ND	
SB-214-308	SB214-6	4	6	5/31/00	192	257	<250	ND	<250	ND	
SB-214-309	SB214-8	6	8	5/31/00	195	101	<250	ND	<250	ND	
SB-214-310	SB214-10	8	10	5/31/00	200	118	<250	ND	<250	ND	
SB-214-311	SB214-12	10	12	5/31/00	197	218	2,500	3.7	<250	ND	
SB-214-312	SB214-14	12	14	5/31/00	203	188	<250	ND	<250	ND	
SB-214-313	SB214-16	14	16	5/31/00	192	185	<250	ND	<250	ND	
SB-214-314	SB214-18	16	18	5/31/00	192	200	173	<250	ND	<250	ND
SB-214-315	SB214-20	18	20	5/31/00	192	232	199	<250	ND	<250	ND
SB-214-316	SB214-22	20	22	5/31/00	194	292	231	<250	ND	<250	ND
SB-214-317	SB214-24	22	24	5/31/00	198	277	133	<250	ND	<250	ND
SB-214-318	SB214-26	24	26	5/31/00	189	230	183	<250	ND	<250	ND
SB-214-319	SB214-28	26	28	5/31/00	190	265	215	<250	ND	<250	ND
SB-214-320	SB214-32	30	32	5/31/00	193	295	217	21,000	31.2	<1,000	ND
SB-214-321	SB214-34	32	34	5/31/00	193	273	218	210,000 D	288.3	<2,500	ND
SB-214-322	SB214-36	34	36	5/31/00	185	246	189	780,000	1,201.7	<25,000	ND
SB-214-323	SB214-38	36	38	5/31/00	196	280	238	80,000	97.5	<1,700	ND
SB-214-324	SB214-40	38	40	5/31/00	194	260	180	460,000	832.0	<12,000	ND
SB-214-325	SB214-42	40	42	5/31/00	194	322	250	260,000	330.3	<8,300	ND
SB-214-326	SB214-44	42	44	5/31/00	193	303	239	12,000	15.5	<250	ND
SB-214-327	SB214-46	44	46	5/31/00	191	317	257	180,000	211.4	<3,600	ND
SB-215-328	SB215-2	0	2	6/1/00	189	214	208	330	0.4	<250	ND
SB-215-329	SB215-4	2	4	6/1/00	196	249	240	350	0.4	<250	ND
SB-215-330	SB215-6	4	6	6/1/00	194	240	146	250	0.6	<250	ND
SB-215-331	SB215-8	6	8	6/1/00	200	158	153	<250	ND	<250	ND
SB-215-332	SB215-10	8	10	6/1/00	197	177	169	670	1.0	<250	ND
SB-215-333	SB215-12	10	12	6/1/00	192	244	207	340	0.5	700.0	0.9
SB-215-334	SB215-14	12	14	6/1/00	192	233	198	<250	ND	<250	ND
SB-215-335	SB215-16	14	16	6/1/00	196	295	257	<250	ND	<250	ND
SB-215-336	SB215-18	16	18	6/1/00	192	324	267	35,000	39.3	<1,200	ND
SB-215-337	SB215-20	18	20	6/1/00	195	194	167	51,000	83.6	<1,800	ND
SB-215-338	SB215-22	20	22	6/1/00	196	307	240	4,700	6.2	<250	ND
SB-215-339	SB215-24	22	24	6/1/00	200	321	264	210,000	246.7	<10,000	ND
SB-215-340	SB215-26	24	26	6/1/00	190	212	173	1,400,000	2,261.9	<50,000	ND
SB-215-341	SB215-28	26	28	6/1/00	191	216	171	5,800,000 D	9,726.8	<83,000	ND

Table C-4. Post-Demo VOC Results of Soil Samples

Preliminary Draft	Sample Depth (ft)	Top Depth	Bottom Depth	Sample Date	Wet Soil Weight (g)	Dry Soil Weight (g)	TCE	cis-1,2-DCE	trans-1,2-DCE	Vinyl chloride
Analytical Sample ID	Sample ID	Top Depth	Bottom Depth	Sample Date	MeOH (g)	Weight (g)	Result in MeOH ( $\mu\text{g/L}$ )	Result in Dry Soil (mg/kg)	Result in MeOH ( $\mu\text{g/L}$ )	Result in Dry Soil (mg/kg)
SB-215-342	SB215-30	28	30	6/1/00	196	198	151	200,000	390.9	<8,300
SB-215-343	SB215-32	30	32	6/1/00	194	267	196	2,100,000	3,391.8	<50,000
SB-215-344	SB215-34	32	34	6/1/00	193	380	298	3,400,000	3,722.9	<83,000
SB-215-349	SB215-34B	32	34	6/1/00	193	367	276	3,200,000 D	3,887.6	<50,000
SB-215-345	SB215-36	34	36	6/1/00	198	270	220	2,400,000	3,279.6	<83,000
SB-215-346	SB215-38	36	38	6/1/00	193	262	217	3,100,000	4,132.9	<62,000
SB-215-347	SB215-40	38	40	6/1/00	200	269	186	4,600,000 D	8,313.7	<83,000
SB-215-348	SB215-42	40	42	6/1/00	195	245	191	530,000	834.8	<25,000
SB-216-130	SB216-2	0	2	5/22/00	195	130	75	<250	ND	<250
SB-216-131	SB216-4	2	4	5/22/00	202	138	93	<250	ND	<250
SB-216-132	SB216-6	4	6	5/22/00	199	134	112	<250	ND	<250
SB-216-218	SB216-8	6	8	5/24/00	200	254	211	<250	ND	2,100
SB-216-219	SB216-10	8	10	5/24/00	192	147	125	<250	ND	460
SB-216-220	SB216-12	10	12	5/24/00	193	182	153	<250	ND	<250
SB-216-221	SB216-14	12	14	5/24/00	197	194	157	<250	ND	<250
SB-216-222	SB216-16	14	16	5/24/00	202	234	178	<250	ND	<250
SB-216-223	SB216-18	16	18	5/24/00	198	254	193	<250	ND	<250
SB-216-224	SB216-20	18	20	5/24/00	192	223	175	<250	ND	<250
SB-216-225	SB216-22	20	22	5/24/00	196	183	146	<250	ND	<250
SB-216-227	SB216-24	22	24	5/24/00	199	290	216	<250	ND	<250
SB-216-228	SB216-26	24	26	5/24/00	203	241	112	530	1.8	<250
SB-216-229	SB216-28	26	28	5/24/00	199	150	115	4,000	10.0	<250
SB-216-226	SB216-28B	26	28	5/24/00	195	250	107	6,500	23.7	<250
SB-216-230	SB216-30	28	30	5/24/00	198	338	273	1,200	1.4	<250
SB-216-231	SB216-32	30	32	5/24/00	195	259	191	3,000	4.9	<250
SB-216-232	SB216-34	32	34	5/24/00	198	267	209	390	0.6	<250
SB-216-233	SB216-36	34	36	5/24/00	203	171	135	<250	ND	960
SB-216-234	SB216-38	36	38	5/24/00	197	265	210	<830	ND	17,000
SB-216-235	SB216-40	38	40	5/24/00	198	339	253	3,100	4.1	6,700
SB-216-236	SB216-42	40	42	5/24/00	199	314	247	2,800	3.6	1,300
SB-216-237	SB216-44	42	44	5/24/00	192	282	230	1,300	1.7	<250
SB-216-238	SB216-46	44	46	5/24/00	204	273	209	<250	ND	<250
SB-217-127	SB217-2	0	2	5/22/00	194	123	94	<250	ND	<250
SB-217-128	SB217-4	2	4	5/22/00	189	133	71	<250	ND	<250
SB-217-129	SB217-6	4	6	5/22/00	191	130	50	<250	ND	<250

**Table C-4. Post-Demo VOC Results of Soil Samples**

Preliminary Draft	Sample Depth (ft)		Sample Date	Wet Soil Weight (g)	Dry Soil Weight (g)	TCE Result in MeOH (µg/L)	cis -1,2-DCE Result in MeOH (µg/kg)	trans -1,2-DCE Result in MeOH (µg/kg)	Vinyl chloride Result in MeOH (µg/L)
	Top Depth	Bottom Depth							
SB-217-170	SB217-8	6	8	5/23/00	197	154	<250	ND	<250
SB-217-171	SB217-10	8	10	5/23/00	194	208	<250	ND	2.7
SB-217-172	SB217-12	10	12	5/23/00	200	161	7,100	<250	<250
SB-217-173	SB217-14	12	14	5/23/00	194	192	149	<250	ND
SB-217-174	SB217-16	14	16	5/23/00	199	196	152	<250	ND
SB-217-175	SB217-18	16	18	5/23/00	201	202	166	<250	ND
SB-217-176	SB217-20	18	20	5/23/00	195	184	143	<250	ND
SB-217-177	SB217-22	20	22	5/23/00	192	257	196	<250	ND
SB-217-178	SB217-24	22	24	5/23/00	193	272	197	350	0.6
SB-217-179	SB217-26	24	26	5/23/00	195	213	164	1,000	1.8
SB-217-180	SB217-28	26	28	5/23/00	199	194	143	8,300	17.6
SB-217-181	SB217-30	28	30	5/23/00	207	194	140	16,000	36.1
SB-217-182	SB217-30B	28	30	5/23/00	199	310	171	34,000	77.7
SB-217-183	SB217-32	30	32	5/23/00	199	310	159	2,700	6.8
SB-217-184	SB217-34	32	34	5/23/00	194	208	160	610	1.1
SB-217-185	SB217-36	34	36	5/23/00	196	240	184	310	0.5
SB-217-186	SB217-38	36	38	5/23/00	199	196	128	8,300	20.7
SB-217-187	SB217-40	38	40	5/23/00	194	230	176	79,000 D	134.5
SB-217-188	SB217-42	40	42	5/23/00	196	209	157	17,000	32.5
SB-217-189	SB217-42 "S"	40	42	5/23/00	201	205	177	15,000	23.9
SB-217-190	SB217-44	42	44	5/23/00	196	317	228	4,400	6.5
SB-217-191	SB217-46	44	46	5/23/00	197	237	169	<250	ND
SB-317-167	SB317-2	0	2	5/22/00	196	151	80	<250	ND
SB-317-166	SB317-4	2	4	5/22/00	196	99	102	<250	ND
SB-317-168	SB317-6	4	6	5/22/00	194	126	76	<250	ND
SB-317-192	SB317-8	6	8	5/23/00	197	150	122	330	0.8
SB-317-193	SB317-10	8	10	5/23/00	195	235	192	2,900	4.4
SB-317-194	SB317-12	10	12	5/23/00	198	179	142	7,300	14.8
SB-317-195	SB317-14	12	14	5/23/00	200	101	82	310	1.0
SB-317-196	SB317-16	14	16	5/23/00	189	198	157	<250	ND
SB-317-197	SB317-18	16	18	5/23/00	196	168	132	<250	ND
SB-317-198	SB317-20	18	20	5/23/00	192	247	190	<250	ND
SB-317-199	SB317-22	20	22	5/23/00	196	240	191	<250	ND
SB-317-200	SB317-24	22	24	5/23/00	198	223	167	<250	ND
SB-317-201	SB317-26	24	26	5/23/00	193	214	167	<250	ND

Table C-4. Post-Demo VOC Results of Soil Samples

Analytical Sample ID	Preliminary Draft Sample ID	Sample Depth (ft)		Sample Date	Wet Soil Weight (g)	Dry Soil Weight (g)	TCE		cis-1,2-DCE		trans-1,2-DCE		Vinyl chloride Result in Dry Soil (mg/kg)
		Top Depth	Bottom Depth				Result in MeOH (µg/L.)	Result in Dry Soil MeOH (mg/kg)	Result in MeOH (µg/L.)	Result in Dry Soil MeOH (mg/kg)	Result in MeOH (µg/L.)	Result in Dry Soil MeOH (mg/kg)	
SB-317-202	SB317-28	26	28	5/23/00	200	265	202	2,800	4.4	<250	ND	<500	ND
SB-317-203	SB317-30	28	30	5/23/00	194	173	129	20,000	44.9	<1,000	ND	<2,000	ND
SB-317-204	SB317-32	30	32	5/23/00	203	236	184	1,100	1.8	<250	ND	<500	ND
SB-317-205	SB317-34	32	34	5/23/00	194	295	230	6,300	8.5	<420	ND	<420	ND
SB-317-206	SB317-36	34	36	5/23/00	195	297	220	20,000	29.4	<1,200	ND	<2,500	ND
SB-317-207	SB317-36B	34	36	5/23/00	193	343	167	23,000	57.9	<1,800	ND	<3,600	ND
SB-317-208	SB317-38	36	38	5/23/00	195	297	149	15,000	39.7	<1,200	ND	<2,500	ND
SB-317-209	SB317-40	38	40	5/23/00	192	249	178	110,000	194.1	<8,300	ND	<17,000	ND
SB-317-210	SB317-42	40	42	5/23/00	198	128	95	4,000	11.9	480.0	1.4	<250	ND
SB-317-211	SB317-44	42	44	5/23/00	201	156	121	3,500	8.4	<250	ND	<500	ND
SB-317-212	SB317-46	44	46	5/23/00	197	242	192	550,000	857.6	<50,000	ND	<100,000	ND
SB-218-118	SB218-2	0	2	5/18/00	203	127	69	<250	ND	<250	ND	<250	ND
SB-218-120	SB218-4	2	4	5/18/00	193	160	103	<250	ND	<250	ND	<500	ND
SB-218-119	SB218-6	4	6	5/18/00	197	136	74	<250	ND	<250	ND	<500	ND
SB-218-148	SB218-8	6	8	5/22/00	200	136	127	<250	ND	<250	ND	<500	ND
SB-218-150	SB218-10	8	10	5/22/00	198	191	162	<250	ND	<250	ND	<500	ND
SB-218-149	SB218-12	10	12	5/22/00	198	164	137	<250	ND	<250	ND	<500	ND
SB-218-151	SB218-14	12	14	5/22/00	193	149	123	<250	ND	<250	ND	<500	ND
SB-218-152	SB218-16	14	16	5/22/00	193	187	153	<250	ND	<250	ND	<500	ND
SB-218-153	SB218-18	16	18	5/22/00	195	165	140	<250	ND	<250	ND	<500	ND
SB-218-154	SB218-20	18	20	5/22/00	199	208	164	<250	ND	<250	ND	<500	ND
SB-218-155	SB218-20B	18	20	5/22/00	195	165	97	<250	ND	<250	ND	<500	ND
SB-218-156	SB218-22	20	22	5/22/00	193	180	142	<250	ND	<250	ND	<500	ND
SB-218-157	SB218-24	22	24	5/22/00	197	183	146	<250	ND	<250	ND	<500	ND
SB-218-158	SB218-26	24	26	5/22/00	193	211	162	2,000	3.6	<250	ND	<500	ND
SB-218-159	SB218-28	26	28	5/22/00	190	201	158	<250	ND	<250	ND	<500	ND
SB-218-160	SB218-30	28	30	5/22/00	192	195	154	<250	ND	<250	ND	<500	ND
SB-218-161	SB218-34	32	34	5/22/00	193	175	109	<250	ND	<250	ND	<500	ND
SB-218-162	SB218-38	36	38	5/22/00	200	225	187	<250	ND	<250	ND	<500	ND
SB-218-163	SB218-40	38	40	5/22/00	196	168	107	<250	ND	<250	ND	<500	ND
SB-218-164	SB218-42	40	42	5/22/00	195	168	124	<250	ND	<250	ND	<500	ND
SB-218-165	SB218-44	42	44	5/22/00	204	198	156	<250	ND	<250	ND	<500	ND
SB-218-169	SB218-46	44	46	5/22/00	196	151	78	<250	ND	<250	ND	<500	ND
SB-219-11	SB219-2	0	2	5/18/00	194	100	96	<250	ND	<250	ND	<500	ND
SB-219-12	SB219-4	2	4	5/18/00	195	153	151	<250	ND	<250	ND	<500	ND

**Table C-4. Post-Demo VOC Results of Soil Samples**

Analytical Sample ID	Preliminary Draft Sample ID	Sample Depth (ft)		Sample Date	Wet Soil Weight (g)	Dry Soil Weight (g)	TCE	cis -1,2-DCE		trans -1,2-DCE		Vinyl chloride Result in MeOH (µg/L)	Result in Dry Soil MeOH (mg/kg)	Result in Dry Soil MeOH (mg/kg)	Result in Dry Soil MeOH (µg/L)	Result in Dry Soil MeOH (mg/kg)	Result in Dry Soil MeOH (µg/L)	Result in Dry Soil MeOH (mg/kg)	Result in Dry Soil MeOH (µg/L)	Result in Dry Soil MeOH (mg/kg)	
		Top Depth	Bottom Depth					Result in MeOH (µg/L)	Result in MeOH (mg/kg)	Result in MeOH (µg/L)	Result in MeOH (mg/kg)										
SB-219-13	SB219-6	4	6	5/18/00	189	159	<250	ND	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND	ND	ND	
SB-219-73	SB219-8	6	8	5/19/00	188	206	165	1,400	2.4	1,000	1.7	<250	ND	<2,100	ND	<2,100	ND	<500	ND	ND	ND
SB-219-74	SB219-10	8	10	5/19/00	200	232	184	35,000	57.3	<2,100	ND	<2,100	ND	<4,200	ND	<4,200	ND	<500	ND	ND	ND
SB-219-75	SB219-12	10	12	5/19/00	193	193	153	23,000	42.7	<750	ND	<750	ND	<1,500	ND	<1,500	ND	<500	ND	<1,000	ND
SB-219-76	SB219-14	12	14	5/19/00	192	190	147	12,000	23.4	<500	ND	<500	ND	<1,000	ND	<1,000	ND	<500	ND	<1,000	ND
SB-219-77	SB219-16	14	16	5/19/00	195	204	169	15,000	25.0	510	0.9	<500	ND	<500	ND	<500	ND	<500	ND	<1,000	ND
SB-219-78	SB219-18	16	18	5/19/00	193	264	214	14,000	19.3	620	0.9	<500	ND	<500	ND	<1,000	ND	<1,000	ND	<500	ND
SB-219-79	SB219-20	18	20	5/19/00	192	251	199	9,900	14.7	850	1.3	<330	ND	<660	ND	<660	ND	<500	ND	<500	ND
SB-219-80	SB219-22	20	22	5/19/00	202	250	207	1,000	1.4	1,300	1.9	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND
SB-219-81	SB219-24	22	24	5/19/00	191	187	137	460	1.0	500	1.1	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND
SB-219-82	SB219-28	26	28	5/19/00	200	254	186	4,800	8.3	940	1.6	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND
SB-219-83	SB219-30	28	30	5/19/00	201	170	86	11,000	43.3	470	1.8	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND
SB-219-84	SB219-32	30	32	5/19/00	190	224	172	7,600	12.9	380	0.6	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND
SB-219-85	SB219-36	34	36	5/19/00	198	214	172	7,700	13.1	260	0.4	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND
SB-219-86	SB219-36B	34	36	5/19/00	196	165	64	6,700	36.5	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND	<500	ND
SB-219-87	SB219-38	36	38	5/20/00	195	178	113	11,000	30.4	270	0.7	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND
SB-219-88	SB219-40	38	40	5/20/00	192	195	141	17,000	35.8	800	1.7	<500	ND	<1,000	ND	<1,000	ND	<500	ND	<500	ND
SB-219-89	SB219-42	40	42	5/20/00	194	177	143	19,000	37.1	<500	ND	<500	ND	<1,000	ND	<1,000	ND	<500	ND	<500	ND
SB-219-90	SB219-44	42	44	5/20/00	199	219	159	43,000	84.3	<1,200	ND	<1,200	ND	<2,500	ND	<2,500	ND	<500	ND	<12,000	ND
SB-219-91	SB219-46	44	46	5/20/00	193	219	134	250,000	614.4	<6,200	ND	<6,200	ND	<500	ND	<500	ND	<500	ND	<500	ND
SB-220-14	SB220-2	0	2	5/18/00	194	163	<250	ND	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND	<500	ND	
SB-220-15	SB220-4	2	4	5/18/00	189	170	163	<250	ND	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND	<500	ND
SB-220-16	SB220-6	4	6	5/18/00	193	189	179	<250	ND	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND	<500	ND
SB-220-92	SB220-8	6	8	5/20/00	200	262	129	<250	ND	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND	<500	ND
SB-220-93	SB220-10	8	10	5/20/00	194	242	195	350	0.5	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND	<500	ND
SB-220-94	SB220-12	10	12	5/20/00	192	267	219	<250	ND	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND	<500	ND
SB-220-95	SB220-14	12	14	5/20/00	198	203	172	<250	ND	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND	<500	ND
SB-220-96	SB220-16	14	16	5/20/00	205	211	180	<250	ND	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND	<500	ND
SB-220-97	SB220-18	16	18	5/20/00	190	217	153	<250	ND	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND	<500	ND
SB-220-98	SB220-20	18	20	5/20/00	192	223	175	<250	ND	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND	<500	ND
SB-220-99	SB220-22	20	22	5/20/00	194	211	167	<250	ND	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND	<500	ND
SB-220-100	SB220-24	22	24	5/20/00	193	203	161	<250	ND	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND	<500	ND
SB-220-101	SB220-26	24	26	5/20/00	195	246	186	<250	ND	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND	<500	ND
SB-220-102	SB220-28	26	28	5/20/00	193	240	183	<250	ND	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND	<500	ND
SB-220-104	SB220-30	28	30	5/20/00	190	186	134	<250	ND	<250	ND	<250	ND	<500	ND	<500	ND	<500	ND	<500	ND

Table C-4. Post-Demo VOC Results of Soil Samples

Preliminary Draft		Sample Depth (ft)		Wet Soil		Dry Soil		TCE		cis -1,2-DCE		trans -1,2-DCE		Vinyl chloride	
Analytical Sample ID	Sample ID	Top Depth	Bottom Depth	Sample Date	MeOH (g)	Weight (g)	Weight (g)	Result in MeOH ( $\mu\text{g/L}$ )	Result in Dry Soil (mg/kg)	Result in MeOH ( $\mu\text{g/L}$ )	Result in Dry Soil (mg/kg)	Result in MeOH ( $\mu\text{g/L}$ )	Result in Dry Soil (mg/kg)	Result in MeOH ( $\mu\text{g/L}$ )	Result in Dry Soil (mg/kg)
SB-220-103	SB220-32	30	32	5/20/00	194	241	191	<250	ND	<250	ND	<250	ND	<500	ND
SB-220-105	SB220-34	32	34	5/20/00	194	232	187	<250	ND	<250	ND	<250	ND	<500	ND
SB-220-106	SB220-34B	32	34	5/20/00	194	242	93	<250	ND	<250	ND	<250	ND	<500	ND
SB-220-107	SB220-36	34	36	5/20/00	193	212	168	<250	ND	<250	ND	<250	ND	<500	ND
SB-220-108	SB220-38	36	38	5/20/00	193	212	183	<250	ND	<250	ND	<250	ND	<500	ND
SB-220-109	SB220-40	38	40	5/20/00	201	242	142	<250	ND	<250	ND	<250	ND	<500	ND
SB-220-110	SB220-42	40	42	5/20/00	193	225	187	<250	ND	<250	ND	<250	ND	<500	ND
SB-220-111	SB220-44	42	44	5/20/00	193	289	230	<250	ND	<250	ND	<250	ND	<500	ND
SB-220-112	SB220-46	44	46	5/20/00	196	245	176	6,000	10.8	<250	ND	<250	ND	<500	ND
SB-221-17	SB221-2	0	2	5/18/00	190	171	166	<250	ND	<250	ND	<250	ND	<500	ND
SB-221-18	SB221-4	2	4	5/18/00	194	259	253	<250	ND	<250	ND	<250	ND	<500	ND
SB-221-19	SB221-6	4	6	5/18/00	195	213	209	<250	ND	<250	ND	<250	ND	<500	ND
SB-221-13	SB221-8	6	8	5/21/00	196	153	133	1,100	2.2	<250	ND	<250	ND	<500	ND
SB-221-14	SB221-10	8	10	5/21/00	194	160	129	<250	ND	<250	ND	<250	ND	<500	ND
SB-221-15	SB221-12	10	12	5/21/00	192	198	156	<250	ND	<250	ND	<250	ND	<500	ND
SB-221-16	SB221-14	12	14	5/21/00	189	269	209	<250	ND	<250	ND	<250	ND	<500	ND
SB-221-17	SB221-16	14	16	5/21/00	249	179	151	<250	ND	<250	ND	<250	ND	<500	ND
SB-221-133	SB221-18	16	18	5/22/00	193	270	210	<250	ND	<250	ND	<250	ND	<500	ND
SB-221-134	SB221-20	18	20	5/22/00	193	297	244	<250	ND	<250	ND	<250	ND	<500	ND
SB-221-135	SB221-22	20	22	5/22/00	191	261	203	<250	ND	<250	ND	<250	ND	<500	ND
SB-221-136	SB221-24	22	24	5/22/00	195	231	182	<250	ND	<250	ND	<250	ND	<500	ND
SB-221-137	SB221-26	24	26	5/22/00	191	180	139	1,800	3.7	<250	ND	<250	ND	<500	ND
SB-221-138	SB221-28	26	28	5/22/00	201	232	170	24,000	44.7	<1,200	ND	<1,200	ND	<2,500	ND
SB-221-139	SB221-30	28	30	5/22/00	201	186	139	32,000	69.4	<2,100	ND	<2,100	ND	<4,200	ND
SB-221-140	SB221-32	30	32	5/22/00	193	214	147	95,000	201.2	<5,000	ND	<5,000	ND	<10,000	ND
SB-221-141	SB221-34	32	34	5/22/00	195	173	137	1,700	3.5	<250	ND	<250	ND	<500	ND
SB-221-142	SB221-36	34	36	5/22/00	199	247	186	650,000	1,093.5	<42,000	ND	<42,000	ND	<84,000	ND
SB-221-143	SB221-38	36	38	5/22/00	192	128	36	44,000	409.5	<2,500	ND	<2,500	ND	<5,000	ND
SB-221-144	SB221-40	38	40	5/22/00	194	193	154	680,000	1,256.5	<42,000	ND	<42,000	ND	<84,000	ND
SB-221-145	SB221-42	40	42	5/22/00	194	159	102	22,000	65.3	<1,200	ND	<1,200	ND	<2,500	ND
SB-221-146	SB221-42B	40	42	5/22/00	194	138	96	19,000	56.9	<1,000	ND	<1,000	ND	<2,000	ND
SB-221-147	SB221-45	43	45	5/22/00	195	172	147	2,300	4.3	<250	ND	<250	ND	<500	ND
SB-223-121	SB223-2	0	2	5/19/00	192	136	76	<250	ND	<250	ND	<250	ND	<500	ND
SB-223-126	SB223-4	2	4	5/19/00	194	134	102	<250	ND	<250	ND	<250	ND	<500	ND
SB-223-122	SB223-6	4	6	5/19/00	195	167	88	<250	ND	<250	ND	<250	ND	<500	ND

**Table C-4. Post-Demo VOC Results of Soil Samples**

Preliminary Draft	Sample ID	Sample Depth (ft)		Sample Date	Wet Soil Weight (g)	Dry Soil Weight (g)	Result in MeOH (µg/L)	Result in TCE (µg/kg)	cis -1,2-DCE		trans -1,2-DCE		Result in MeOH (µg/L)	Result in Dry Soil MeOH (mg/kg)	Result in Vinyl chloride in Dry Soil (mg/kg)
		Top Depth	Bottom Depth						Result in MeOH (µg/L)	Result in Dry Soil MeOH (mg/kg)	Result in MeOH (µg/L)	Result in Dry Soil MeOH (mg/kg)			
SB-223-53	SB223-8	6	8	5/19/00	198	153	122	2,300	5.3	260	0.6	<250	ND	<500	ND
SB-223-54	SB223-10	8	10	5/19/00	192	86	71	2,100	7.6	<250	ND	<250	ND	<500	ND
SB-223-55	SB223-12	10	12	5/19/00	196	187	150	21,000	39.9	<500	ND	<500	ND	<1,000	ND
SB-223-56	SB223-14	12	14	5/19/00	194	156	124	20,000	44.8	<500	ND	<500	ND	<1,000	ND
SB-223-57	SB223-16	14	16	5/19/00	194	216	184	<250	ND	<250	ND	<250	ND	<500	ND
SB-223-58	SB223-18	16	18	5/19/00	191	194	145	3,100	6.2	<250	ND	<250	ND	<500	ND
SB-223-59	SB223-20	18	20	5/19/00	192	217	173	<250	ND	<250	ND	<250	ND	<500	ND
SB-223-60	SB223-22	20	22	5/19/00	191	201	152	46,000	88.0	<2,500	ND	<2,500	ND	<5,000	ND
SB-223-61	SB223-24	22	24	5/19/00	194	189	148	16,000	31.0	<750	ND	<750	ND	<1,500	ND
SB-223-62	SB223-26	24	26	5/19/00	198	192	143	1,900	4.0	<250	ND	<250	ND	<500	ND
SB-223-63	SB223-28	26	28	5/19/00	193	216	151	3,500	7.2	350	0.7	<250	ND	<500	ND
SB-223-64	SB223-30	28	30	5/19/00	192	261	187	6,900	11.7	890	1.5	<330	ND	<660	ND
SB-223-65	SB223-32	30	32	5/19/00	196	215	161	1,700	3.2	<250	ND	<250	ND	<500	ND
SB-223-66	SB223-34	32	34	5/19/00	198	239	193	<250	ND	<250	ND	<250	ND	<500	ND
SB-223-67	SB223-34B	32	34	5/19/00	194	185	110	4,100	11.9	330	1.0	<250	ND	<500	ND
SB-223-68	SB223-36	34	36	5/19/00	195	183	139	<250	ND	<250	ND	<250	ND	<500	ND
SB-223-69	SB223-38	36	38	5/19/00	195	248	177	40,000	71.8	<2,100	ND	<2,100	ND	<4,200	ND
SB-223-70	SB223-40	38	40	5/19/00	196	240	174	12,000	21.7	1,400	2.5	<500	ND	<1,000	ND
SB-223-71	SB223-42	40	42	5/19/00	193	203	152	2,900	5.6	410	0.8	<250	ND	<500	ND
SB-223-72	SB223-45	42	45	5/19/00	194	204	151	47,000	92.9	<2,500	ND	<2,500	ND	<5,000	ND
SB-224-20	SB224-2	0	2	5/18/00	194	130	130	<250	ND	<250	ND	<250	ND	<500	ND
SB-224-21	SB224-4	2	4	5/18/00	193	117	115	<250	ND	<250	ND	<250	ND	<500	ND
SB-224-22	SB224-6	4	6	5/18/00	193	209	204	<250	ND	<250	ND	<250	ND	<500	ND
SB-224-32	SB224-8	6	8	5/18/00	193	127	103	<250	ND	<250	ND	<250	ND	<500	ND
SB-224-33	SB224-10	8	10	5/18/00	197	198	163	<250	ND	<250	ND	<250	ND	<500	ND
SB-224-34	SB224-12	10	12	5/18/00	189	198	161	<250	ND	<250	ND	<250	ND	<500	ND
SB-224-36	SB224-14	12	14	5/18/00	195	255	183	<250	ND	<250	ND	<250	ND	<500	ND
SB-224-37	SB224-16	14	16	5/18/00	193	256	211	<250	ND	<250	ND	<250	ND	<500	ND
SB-224-38	SB224-18	16	18	5/18/00	195	217	166	<250	ND	<250	ND	<250	ND	<500	ND
SB-224-39	SB224-20	18	20	5/18/00	193	217	165	<250	ND	<250	ND	<250	ND	<500	ND
SB-224-40	SB224-22	20	22	5/18/00	193	181	119	<250	ND	<250	ND	<250	ND	<500	ND
SB-224-41	SB224-24	22	24	5/18/00	194	233	169	<250	ND	<250	ND	<250	ND	<500	ND
SB-224-42	SB224-26	24	26	5/18/00	193	202	150	<250	ND	<250	ND	<250	ND	<500	ND
SB-224-43	SB224-28	26	28	5/18/00	194	248	186	120,000	198.4	<3,600	ND	<3,600	ND	<7,200	ND
SB-224-44	SB224-30	28	30	5/18/00	194	297	217	2,800,000	4,200.9	<62,000	ND	<62,000	ND	<120,000	ND

Table C-4. Post-Demo VOC Results of Soil Samples

Analytical Sample ID	Preliminary Draft Sample ID	Sample Depth (ft)		Sample Date	Wet Soil Weight (g)	Dry Soil Weight (g)	TCE		<i>cis</i> -1,2-DCE		<i>trans</i> -1,2-DCE		Vinyl chloride Result in MeOH (µg/L)	Result in Dry Soil (mg/kg)	Result in Dry Soil (mg/kg)
		Top Depth	Bottom Depth				Result in MeOH (µg/L)	Result in Dry Soil MeOH (mg/kg)	Result in MeOH (µg/L)	Result in Dry Soil MeOH (mg/kg)	Result in MeOH (µg/L)	Result in Dry Soil MeOH (mg/kg)			
SB-224-45	SB224-32	30	32	5/18/00	197	242	191	140,000	220.2	<5,000	ND	<5,000	ND	<10,000	ND
SB-224-46	SB224-34	32	34	5/18/00	194	294	217	200,000	297.3	<8,300	ND	<8,300	ND	<17,000	ND
SB-224-47	SB224-36	34	36	5/19/00	196	174	126	45,000	105.8	<1,200	ND	<1,200	ND	<2,500	ND
SB-224-48	SB224-38	36	38	5/19/00	190	127	86	85,000	278.2	<2,500	ND	<2,500	ND	<5,000	ND
SB-224-50	SB224-38B	36	38	5/19/00	382	186	141	720,000	2,698.9	<25,000	ND	<25,000	ND	<50,000	ND
SB-224-51	SB224-40	38	40	5/19/00	193	143	114	52,000	124.7	<1,200	ND	<1,200	ND	<2,500	ND
SB-224-52	SB224-42	40	42	5/19/00	190	187	142	290,000	583.1	<10,000	ND	<10,000	ND	<20,000	ND
SB-224-49	SB224-45	42	45	5/19/00	189	214	169	110,000	185.0	<2,500	ND	<2,500	ND	<5,000	ND
SB-225-123	SB225-2	0	2	5/18/00	193	132	92	<250	ND	<250	ND	<250	ND	<250	ND
SB-225-124	SB225-4	2	4	5/18/00	194	139	82	<250	ND	<250	ND	<250	ND	<250	ND
SB-225-125	SB225-6	4	6	5/18/00	194	134	90	<250	ND	<250	ND	<250	ND	<250	ND
SB-225-1	SB225-8	6	8	5/18/00	193	235	196	<250	ND	750	1.1	<250	ND	<250	ND
SB-225-2	SB225-12	10	12	5/18/00	192	188	157	14,000	24.4	<500	ND	<500	ND	<500	ND
SB-225-3	SB225-14	12	14	5/18/00	195	163	135	760	1.5	<250	ND	<250	ND	<250	ND
SB-225-4	SB225-16	14	16	5/18/00	197	191	164	<250	ND	<250	ND	<250	ND	<250	ND
SB-225-5	SB225-18	16	18	5/18/00	197	299	258	<250	ND	<250	ND	<250	ND	<250	ND
SB-225-6	SB225-20	18	20	5/18/00	194	244	202	840	1.2	370.0	0.5	<250	ND	<1,000	ND
SB-225-7	SB225-22	20	22	5/18/00	185	201	163	<250	ND	<250	ND	<250	ND	<250	ND
SB-225-8	SB225-24	22	24	5/18/00	187	266	211	1,700	2.4	1,400	1.9	<250	ND	<250	ND
SB-225-9	SB225-26	24	26	5/18/00	190	270	208	4,600	6.7	1,200	1.7	<250	ND	<250	ND
SB-225-10	SB225-28	26	28	5/18/00	193	299	214	9,900	15.2	2,000	3.1	<500	ND	<250	ND
SB-225-23	SB225-30	28	30	5/18/00	192	192	136	5,900	13.0	910	2.0	<250	ND	<250	ND
SB-225-24	SB225-32	30	32	5/18/00	191	225	170	320	0.6	<250	ND	<250	ND	<250	ND
SB-225-25	SB225-34	32	34	5/18/00	194	255	194	<250	ND	<250	ND	<250	ND	<250	ND
SB-225-26	SB225-36	34	36	5/18/00	191	284	207	<250	ND	<250	ND	<250	ND	<250	ND
SB-225-27	SB225-38	36	38	5/18/00	191	210	135	1,700	4.0	<250	ND	<250	ND	<250	ND
SB-225-28	SB225-40	38	40	5/18/00	196	218	169	9,300	16.3	2,700	4.7	<250	ND	<250	ND
SB-225-29	SB225-40B	38	40	5/18/00	193	179	86	4,700	18.4	1,500	5.9	<250	ND	<250	ND
SB-225-30	SB225-42	40	42	5/18/00	197	187	136	1,800	4.0	700	1.5	<250	ND	<250	ND
SB-225-31	SB225-44	42	44	5/18/00	192	177	133	430	0.9	<250	ND	<250	ND	<250	ND
SB-225-35	SB225-46	44	46	5/18/00	197	205	152	110,000	218.8	<3,600	ND	<3,600	ND	<7,200	ND
SB-226-259	SB26-2	0	2	5/24/00	193	127	124	<250	ND	<250	ND	<250	ND	<250	ND
SB-226-260	SB26-4	2	4	5/24/00	193	181	179	<250	ND	<250	ND	<250	ND	<500	ND
SB-226-261	SB26-6	4	6	5/24/00	193	164	157	<250	ND	<250	ND	<250	ND	<500	ND
SB-226-262	SB26-8	6	8	5/25/00	193	127	73	<250	ND	<250	ND	<250	ND	<500	ND

**Table C-4. Post-Demo VOC Results of Soil Samples**

Preliminary Draft		Sample Depth (ft)		Wet Soil		Dry Soil		TCE		cis -1,2-DCE		trans -1,2-DCE		Vinyl chloride	
Analytical Sample ID	Sample ID	Top Depth	Bottom Depth	Sample Date	MeOH Weight (g)	Weight (g)	MeOH	Result in MeOH (µg/L)	Result in Dry Soil (mg/kg)	Result in MeOH (µg/L)	Result in Dry Soil (mg/kg)	Result in MeOH (µg/L)	Result in Dry Soil (mg/kg)	Result in MeOH (µg/L)	Result in Dry Soil (mg/kg)
SB-26-263	SB26-10	8	10	5/25/00	193	194	110	<250	ND	<250	ND	<250	ND	<500	ND
SB-26-264	SB26-12	10	12	5/25/00	193	219	181	<250	ND	<250	ND	<250	ND	<500	ND
SB-26-265	SB26-14	12	14	5/25/00	193	197	168	5,200	8.5	<250	ND	<250	ND	<500	ND
SB-26-266	SB26-16	14	16	5/25/00	193	241	199	19,000	27.3	<830	ND	<830	ND	<1,700	ND
SB-26-267	SB26-18	16	18	5/25/00	196	222	174	<250	ND	<250	ND	<250	ND	<500	ND
SB-26-268	SB26-20	18	20	5/25/00	199	249	203	40,000	58.7	<1,000	ND	<1,000	ND	<2,000	ND
SB-26-269	SB26-22	20	22	5/25/00	194	185	147	90,000	173.6	<3,100	ND	<3,100	ND	<6,200	ND
SB-26-270	SB26-24	22	24	5/25/00	193	241	184	180,000 D	294.8	<3,600	ND	<3,600	ND	<7,200	ND
SB-26-276	SB26-26	24	26	5/25/00	193	244	191	520,000	809.4	<25,000	ND	<25,000	ND	<50,000	ND
SB-26-277	SB26-28	26	28	5/25/00	194	285	210	290,000	442.7	<12,000	ND	<12,000	ND	<25,000	ND
SB-26-278	SB26-30	28	30	5/25/00	194	246	140	270,000	678.0	<12,000	ND	<12,000	ND	<25,000	ND
SB-26-279	SB26-32	30	32	5/25/00	192	199	160	160,000	282.0	<5,000	ND	<5,000	ND	<10,000	ND
SB-26-280	SB26-34	32	34	5/25/00	193	165	129	120,000	260.7	<5,000	ND	<5,000	ND	<10,000	ND
SB-26-281	SB26-34B	32	34	5/25/00	195	235	103	160,000	588.5	<8,300	ND	<8,300	ND	<17,000	ND
SB-26-282	SB26-36	34	36	5/25/00	195	235	132	160,000	424.0	<5,000	ND	<5,000	ND	<10,000	ND
SB-26-283	SB26-38	36	38	5/25/00	192	217	157	190,000	366.7	<8,300	ND	<8,300	ND	<17,000	ND
SB-26-284	SB26-40	38	40	5/25/00	194	370	271	320,000	406.9	<12,000	ND	<12,000	ND	<25,000	ND
SB-26-285	SB26-42	40	42	5/25/00	195	411	294	5,000,000	6,187.7	<100,000	ND	<100,000	ND	<200,000	ND
SB-26-286	SB26-44	42	44	5/25/00	200	247	199	2,900,000 D	4,388.8	<62,000	ND	<62,000	ND	<120,000	ND
SB-26-287	SB26-46	44	46	5/25/00	197	199	150	2,000,000	3,978.2	<62,000	ND	<62,000	ND	<120,000	ND
SB-27-271	SB27-2	0	2	5/25/00	195	110	113	<250	ND	<250	ND	<250	ND	<500	ND
SB-27-272	SB27-4	2	4	5/25/00	195	158	158	<250	ND	<250	ND	<250	ND	<500	ND
SB-27-273	SB27-6	4	6	5/25/00	196	101	96	<250	ND	<250	ND	<250	ND	<500	ND
SB-27-274	SB27-8	6	8	5/25/00	192	227	182	<250	ND	<250	ND	<250	ND	<500	ND
SB-27-275	SB27-10	8	10	5/25/00	202	278	224	<250	ND	<250	ND	<250	ND	<500	ND
SB-27-288	SB27-12	10	12	5/25/00	196	179	143	6,400	12.7	500	1.0	<330	ND	<660	ND
SB-27-289	SB27-14	12	14	5/25/00	199	208	170	420	0.7	<250	ND	<250	ND	<500	ND
SB-27-290	SB27-14B	12	14	5/25/00	199	282	99	3,000	13.2	<250	ND	<250	ND	<500	ND
SB-27-291	SB27-16	14	16	5/25/00	200	208	118	860	2.5	<250	ND	<250	ND	<500	ND
SB-27-292	SB27-18	16	18	5/25/00	202	187	163	3,000	5.1	<250	ND	<250	ND	<500	ND
SB-27-293	SB27-20	18	20	5/25/00	195	257	207	54,000	77.4	<2,500	ND	<2,500	ND	<5,000	ND
SB-27-294	SB27-22	20	22	5/25/00	197	223	175	110,000	186.9	<5,000	ND	<5,000	ND	<10,000	ND
SB-27-295	SB27-24	22	24	5/25/00	197	206	160	130,000	240.0	6,700	12.4	<5,000	ND	<10,000	ND
SB-27-296	SB27-24 'S'	22	24	5/25/00	193	238	128	140,000	387.5	8,500	23.5	<5,000	ND	<10,000	ND
SB-27-297	SB27-26	24	26	5/25/00	192	263	136	160,000	435.3	<6,200	ND	<6,200	ND	<12,000	ND

Table C-4. Post-Demo VOC Results of Soil Samples

Preliminary Draft	Sample Depth (ft)	Top Depth	Bottom Depth	Sample Date	Wet Soil Weight (g)	Dry Soil Weight (g)	TCE	cis -1,2-DCE	trans -1,2-DCE	Vinyl chloride
Analytical Sample ID	Sample ID				MeOH (µg/L)	Dry Soil MeOH (mg/kg)	Result in MeOH (µg/L)	Result in Dry Soil MeOH (mg/kg)	Result in Dry Soil MeOH (µg/L)	Result in Dry Soil MeOH (mg/kg)
SB-27-298	SB27-28	26	28	5/25/00	194	226	171	210,000 D	369.1	6.2
SB-27-299	SB27-32	30	32	5/25/00	204	323	247	120,000	162.4	<250
SB-27-300	SB27-34	32	34	5/25/00	193	216	115	29,000	87.1	29,000
SB-27-301	SB27-36	34	36	5/25/00	193	329	173	48,000	111.1	102.1
SB-27-302	SB27-38	36	38	5/25/00	189	317	145	48,000	136.1	34,000
SB-27-303	SB27-40	38	40	5/25/00	193	321	151	130,000 D	356.7	16,000
SB-27-304	SB27-42	40	42	5/25/00	194	384	154	220,000	679.4	<8,300
SB-27-305	SB27-45	43	45	5/26/00	190	246	160	820,000	1,673.3	<30,000
SB-28-350	SB-28-2	0	2	6/2/00	195	234	82	1,500	7.3	<250
SB-28-351	SB-28-4	2	4	6/2/00	191	233	73	4,600	25.3	<250
SB-28-352	SB-28-6	4	6	6/2/00	192	131	87	7,100	23.4	<250
SB-28-353	SB-28-8	6	8	6/2/00	191	205	110	<250	ND	<250
SB-28-354	SB-28-10	8	10	6/2/00	194	192	124	<250	ND	<250
SB-28-355	SB-28-12	10	12	6/2/00	197	226	116	2,900	9.0	2.5
SB-28-356	SB-28-14	12	14	6/2/00	197	169	79	6,600	28.4	1,600
SB-28-357	SB-28-14B	12	14	6/2/00	194	193	69	4,700	25.2	1,700
									9.1	<250

Notes:

NA: Not available.

ND: Not detected.

<: Result was not detected at or above the stated reporting limit.

D: Result was obtained from the analysis of a dilution.

DC: Ditch Core.

\*S: Spiked sample

**Figure C-1. TCE Concentrations and Soil Color Results from the Oxidation Plot Soil Cores**

Top Depth	Bottom Depth	PA-1 (mg/Kg)	PA-201 (mg/Kg)	PA-2 (mg/Kg)	PA-202 (mg/Kg)	PA-5 (mg/Kg)	PA-205 (mg/Kg)	PA-6 (mg/Kg)	PA-206 (mg/Kg)
0	2	NA	8.6	NA	2	NA	ND	NA	NA
2	4	NA	ND	NA	1	NA	ND	NA	1.7
4	6	NA	0.7	NA	ND	NA	ND	NA	ND
6	8	NA	1.2	NA	2	NA	ND	NA	ND
8	10	NA	ND	NA	ND	NA	0.6	NA	ND
10	12	NA	ND	NA	2	NA	ND	NA	2.3
12	14	NA	1.5	NA	1	NA	3.4	NA	1.6
14	16	NA	4.6	NA	0	2.5	ND	0.3	0.5
16	18	NA	0.9	NA	694	1.0	136	1.9	35
18	20	NA	2.6	4,513	21	5.4	127	21	124
20	22	NA	6.6	316	156	2	41	83	86
22	24	NA	12.8	275	598	91	27	NA	144
24	26	NA	ND	336	798	193	65	179	202
26	28	NA	ND	293	346	125	58	255	237
28	30	NA	ND	223	3,858	15	39	164	233
30	32	NA	ND	NA	13,100	73	31	131	81
32	34	NA	ND	2,570	2,039	1.3	ND	137	45
34	36	0.3	ND	814	4,886	NA	ND	112	189
36	38	NA	ND	218	681	1.1	6.3	39	170
38	40	NA	ND	271	416	2.3	19.8	5	214
40	42	2.9	ND	2,792	NA	8.2	48.8	56	71
42	44	NA	ND	1,096	444	27	5.1	74	0.7
44	46	NA	ND	NA	472	8.2	NA	33	0.3

Top Depth	Bottom Depth	PA-7 (mg/Kg)	PA-207 (mg/Kg)	PA-8 (mg/Kg)	PA-208 (mg/Kg)	PA-9 (mg/Kg)	PA-209 (mg/Kg)	PA-11 (mg/Kg)	PA-211 (mg/Kg)
0	2	NA	1.3	NA	3.5	NA	NA	NA	3.3
2	4	NA	4.1	NA	1.2	NA	ND	NA	NA
4	6	NA	1.1	NA	0.9	NA	ND	NA	2.5
6	8	NA	1.0	NA	ND	NA	ND	NA	3.5
8	10	NA	3.8	NA	ND	NA	ND	NA	0.5
10	12	NA	8.6	NA	0.3	NA	3.6	NA	1
12	14	NA	10	NA	ND	NA	36	NA	14
14	16	0.5	89	0.9	ND	6	51	NA	27
16	18	1.4	89	0.5	ND	92	56	NA	32
18	20	0.4	5	1.1	31	156	81	5.5	3.2
20	22	2.9	12	38	32	188	89	NA	3.4
22	24	75	2.6	6.3	102	205	46	207	3,332
24	26	6.9	ND	175	255	9.1	37	250	123
26	28	46	1.6	77	108	58.4	ND	228	958
28	30	6.1	1.1	67	32	14.7	ND	236	186
30	32	0.5	29	32	92	0.6	ND	185	468
32	34	0.3	18.4	53	58	0.2	2.9	483	300
34	36	0.1	ND	41	34	3.0	1.3	363	208
36	38	1.2	7.9	1	44	0.1	7.1	142	206
38	40	0.2	ND	2	138	1.6	61	NA	961
40	42	0.7	ND	21	147	NA	61	NA	2,357
42	44	NA	ND	95	261	41.7	NA	NA	241
44	46	0.1	0.8	115	234	1.2	NA	NA	NA

NA: Not available.

ND: Not detected.

Solid horizontal lines demarcate MFGU.

**Figure C-1. TCE Concentrations and Soil Color Results from the Oxidation Plot Soil Cores**

Top Depth	Bottom Depth	PA-12 (mg/Kg)	PA-212 (mg/Kg)	LC34B09 (mg/Kg)	LC34B209 (mg/kg)	LC34B309 (mg/kg)	LC34B39 (mg/Kg)	LC34B239 (mg/Kg)
0	2	NA	ND	NA	ND	ND	NA	0.8
2	4	NA	0.8	NA	ND	ND	NA	0.4
4	6	NA	0.9	NA	1	ND	NA	0.3
6	8	NA	1.0	NA	3	ND	NA	1.3
8	10	NA	1.1	NA	18	ND	NA	6
10	12	NA	2.2	NA	28	ND	NA	12
12	14	NA	ND	NA	50	3	NA	9
14	16	NA	ND	ND	28	ND	NA	4
16	18	NA	ND	ND	3	ND	NA	9
18	20	NA	ND	ND	23	ND	NA	16
20	22	30	ND	0.001	53	ND	NA	5
22	24	31	87	0.004	41	ND	NA	346
24	26	154	34	0.069	6	ND	0.1	222
26	28	126	305	0.1	1	ND	NA	298
28	30	201	327	0.025	3	ND	NA	358
30	32	NA	307	0.009	1	ND	NA	289
32	34	130	209	0.007	3	ND	NA	314
34	36	125	176	ND	ND	ND	NA	247
36	38	178	314	ND	4	ND	NA	284
38	40	NA	123	ND	ND	ND	NA	158
40	42	73	149	0.001	ND	ND	0.1	NA
42	44	98	97	ND	2	ND	0.1	267
44	46	196	NA	ND	NA	ND	0.2	265

Top Depth	Bottom Depth	LC34B17 (mg/Kg)	LC34B217 (mg/kg)	LC34B14 (mg/Kg)	LC34B214 (mg/kg)	LC34B314 (mg/kg)
0	2	NA	ND	NA	ND	ND
2	4	NA	ND	NA	ND	ND
4	6	NA	1	NA	ND	ND
6	8	NA	1	NA	ND	ND
8	10	NA	13	NA	ND	5
10	12	NA	11	ND	ND	5
12	14	NA	14	ND	ND	6
14	16	NA	6	ND	71	12
16	18	NA	ND	ND	4	16
18	20	NA	ND	ND	1	3
20	22	0.1	8	ND	10	ND
22	24	0.0	96	ND	3	ND
24	26	0.0	160	ND	ND	ND
26	28	0.0	223	ND	ND	ND
28	30	ND	67	ND	ND	ND
30	32	ND	27	ND	ND	ND
32	34	ND	NA	ND	ND	ND
34	36	ND	ND	ND	ND	ND
36	38	ND	ND	ND	ND	1
38	40	ND	NA	ND	ND	ND
40	42	ND	ND	ND	NA	ND
42	44	0.062	NA	ND	NA	0
44	46	0.017	NA	ND	NA	NA

NA: Not available.

ND: Not detected.

Solid horizontal lines demarcate MFGU.

## **Appendix D. Inorganic and Other Aquifer Parameters**

Tables D-1 to D-7

**Table D-1. Groundwater Field Parameters**

Well ID	pH						ORP (mV)					
	Pre-Demo	Week 3-4	Week 7-8	Jan. 2000	Apr 2000	OX Post-Demo	Pre-Demo	Week 3-4	Week 7-8	Jan. 2000	Apr 2000	OX Post-Demo
<b>Oxidation Plot Wells</b>												
BAT-1S	7.29	NA	NA	NA	NA	NA	-116.7	NA	NA	NA	NA	NA
BAT-1I	7.60	NA	NA	NA	NA	NA	-142.4	NA	NA	NA	NA	NA
BAT-1D	7.53	NA	NA	NA	NA	NA	-138.3	NA	NA	NA	NA	NA
BAT-2S	7.33	8.07	7.95	7.65	NM	NM	-115.3	579.5	471.8	70.4	NM	NM
BAT-2I	7.50	NA	7.08	8.40	NM	NM	-149.1	NA	396.1	71.1	NM	384.2
BAT-2D	7.47	NA	6.57	6.63	NM	NM	-143.6	NA	211.8	129.9	NM	NM
BAT-3S	7.38	NA	NA	NA	NA	NA	-138.2	NA	NA	NA	NA	NA
BAT-3I	7.60	NA	NA	NA	NA	6.56	-153.1	NA	NA	NA	NA	-96.7
BAT-3D	7.52	NA	NA	NA	NA	NA	-150.1	NA	NA	NA	NA	NA
BAT-5S	7.01	6.92	6.97	8.34	7.21	7.16	-148.7	172.8	334.9	91.3	-93.5	-2.0
BAT-5I	7.50	NA	7.64	8.42	NM	NM	-164.5	NA	250.5	145.2	NM	NM
BAT-5D	7.50	NA	7.18	7.65	6.87	6.41	-130.9	NA	108.4	172.1	39.0	-83.6
BAT-6S	7.36	NA	NA	NA	NA	NA	-137.3	NA	NA	NA	NA	NA
BAT-6I	7.60	NA	NA	NA	NA	NA	-160.6	NA	NA	NA	NA	NA
BAT-6D	7.52	NA	NA	NA	NA	NA	-146.3	NA	NA	NA	NA	NA
PA-4S	7.10	NA	NA	NA	NA	NA	-25.2	NA	NA	NA	NA	NA
PA-4I	7.26	NA	NA	NA	NA	NA	-37.6	NA	NA	NA	NA	NA
PA-4D	7.41	NA	NA	NA	NA	NA	-22.2	NA	NA	NA	NA	NA
<b>Oxidation Perimeter Wells</b>												
PA-3S	7.08	7.02	6.87	8.25	NM	NM	-34.9	-87.9	149.5	100.2	NM	NM
PA-3I	7.57	7.62	7.11	7.72	7.09	6.09	-27.7	-51.0	41.4	153.0	-331.9	-95.0
PA-3D	7.19	7.47	7.03	9.57	NM	NM	-90.3	-53.7	-36.9	156.9	NM	NM
PA-5S	7.18	7.20	7.13	7.28	6.86	NM	-47.9	-30.5	-5.2	-115.9	-78.2	NM
PA-5I	7.10	7.26	7.08	7.42	7.11	6.88	-79.7	-123.6	-100.8	-98.9	-85.0	-82.1
PA-5D	7.47	7.66	7.45	7.73	7.53	7.39	-62.7	-86.9	-71.8	-113.9	-223.2	-153.3
PA-6S	7.17	7.26	7.14	7.90	7.84	7.91	-75.2	-155.8	-137.1	136.0	-149.8	-52.8
PA-6I	7.45	7.50	7.44	7.87	7.53	7.38	-26.0	-77.4	-76.8	55.6	-150.2	-30.1
PA-6D	7.41	7.52	7.46	7.61	7.49	7.46	-73.0	-128.4	-57.9	61.7	-174.5	-143.5
PA-9S	7.47	7.51	7.39	7.82	8.64	7.29	-32.3	-93.4	-14.0	-100.7	9.1	-89.6
PA-9I	7.43	7.65	7.49	7.88	7.39	7.42	-31.4	-120.9	-98.4	-157.8	-94.0	-70.6
PA-9D	7.42	7.65	7.53	7.89	7.33	7.37	-73.4	-83.5	-50.4	-121.0	-215.9	-107.5
PA-12S	7.03	7.18	7.04	6.44	7.02	6.82	-135.4	-128.2	-133.2	-123.0	-124.3	-97.9
PA-12I	7.42	7.54	7.41	7.89	7.27	7.30	-138.8	-126.2	-126.2	-174.4	-140.3	-109.5
PA-12D	7.49	7.50	7.33	7.76	6.91	6.87	-151.0	-120.7	-125.9	-187.1	-169.4	-136.1
<b>SPH Plot Wells</b>												
PA-13S	6.87	6.29	NA	NA	7.04	NA	-107.9	-83.7	NA	NA	-286.1	NA
PA-13I	7.38	7.81	NA	NA	8.41	NA	-73.9	-146.8	NA	NA	-82.5	NA
PA-13D	7.24	7.98	NA	NA	8.50	NA	-105.8	-71.4	NA	NA	-111.6	NA
PA-14S	7.13	9.15	NA	NA	6.72	NA	-129.6	-196.3	NA	NA	-208.0	NA
PA-14I	7.51	8.89	NA	NA	6.62	NA	-118.3	-151.9	NA	NA	-260.1	NA
PA-14D	7.45	7.57	NA	NA	NA	NA	-141.7	-58.5	NA	NA	-231.0	NA
<b>SPH Perimeter Wells</b>												
PA-2S	6.94	7.37	NA	7.50	6.90	6.62	-58.3	-138.5	NA	-97.6	-277.7	-153.1
PA-2I	7.30	6.50	NA	7.50	6.77	6.75	-31.9	-68.9	NA	-127.0	-102.6	-134.7

**Table D-1. Groundwater Field Parameters (Continued)**

Well ID	pH						ORP (mV)					
	Pre-Demo	Week 3-4	Week 7-8	Jan. 2000	Apr 2000	OX Post-Demo	Pre-Demo	Week 3-4	Week 7-8	Jan. 2000	Apr 2000	OX Post-Demo
PA-2D	7.27	6.99	NA	7.46	4.10?	7.00	-89.8	-163.6	NA	-132.0	-75.7	-112.6
PA-7S	6.86	6.59	NA	7.14	6.60	NA	-82.5	-111.2	NA	-121.6	-157.0	NA
PA-7I	7.31	7.26	NA	7.51	6.85	NA	-33.9	-80.3	NA	-120.4	-89.4	NA
PA-7D	7.49	7.00	NA	7.14	7.81	NA	-56.1	-144.0	NA	-127.9	-58.3	NA
PA-10S	6.78	6.72	NA	6.98	6.63	NA	-119.5	-99.2	NA	-142.8	-121.9	NA
PA-10I	6.86	6.72	NA	6.81	6.63	NA	-129.7	-99.8	NA	-132.4	-125.2	NA
PA-10D	7.37	6.48	NA	6.87	7.04	NA	-131.1	46.2	NA	-125.4	-89.4	NA
IW-17S	6.79	5.93	NA	7.85	Dry	NA	-12.4	-29.5	NA	-122.3	Dry	NA
IW-17I	7.41	6.92	NA	6.83	6.20	NA	-12.3	-96.6	NA	-132.5	-76.9	NA
IW-17D	7.39	NA	NA	8.43	7.56	NA	-115.8	-242.3	NA	-144.5	-85.7	NA
PA-15	NA	NA	NA	6.86	6.37	NA	NA	NA	NA	-154.1	-190.4	NA
<b>Distant Wells</b>												
PA-1S	7.58	7.79	7.65	8.15	7.54	7.29	-57.4	1.6	148.2	43.4	-55.0	-117.1
PA-1I	7.72	8.39	NM	8.27	7.64	7.60	-13.3	-19.5	54.8	-94.6	3.1	-65.3
PA-1D	7.57	7.88	7.90	7.97	7.52	7.50	-112.2	-13.4	-762.4	-124.8	-66.8	-90.1
PA-8S	6.93	7.08	7.22	6.87	6.66	6.54	-96.2	-61.8	-115.9	209.6	-33.4	-58.4
PA-8I	7.27	7.41	7.52	7.43	7.21	7.16	-6.6	4.3	-31.8	109.5	-99.2	-114.8
PA-8D	7.45	7.66	7.73	7.85	6.86	6.78	-19.0	9.0	-50.7	87.0	-123.8	-52.8
PA-11S	7.02	6.95	6.75	7.45	6.37	NM	-124.8	-77.8	-76.0	-152.1	-71.3	NM
PA-11I	7.11	7.25	7.07	7.24	7.01	6.22	-136.4	-93.9	-133.5	-127.2	-86.0	-75.9
PA-11D	7.55	7.69	7.41	7.71	7.45	7.46	-136.3	-73.2	-96.7	-156.4	-143.9	-133.3

**Table D-1. Groundwater Field Parameters (Continued)**

Well ID	DO (mg/L)						Temperature (°C)					
	Pre-Demo	Week 3-4	Week 7-8	Jan. 2000	Apr 2000	OX Post-Demo	Pre-Demo	Week 3-4	Week 7-8	Jan. 2000	Apr 2000	OX Post-Demo
<b>Oxidation Plot Wells</b>												
BAT-1S	2.73	NA	NA	NA	NA	NA	26.84	NA	NA	NA	NA	NA
BAT-1I	0.61	NA	NA	NA	NA	NA	26.51	NA	NA	NA	NA	NA
BAT-1D	NA	NA	NA	NA	NA	NA	26.77	NA	NA	NA	NA	NA
BAT-2S	0.38	NM	1.91	NM	NM	NM	26.85	29.33	28.75	23.48	NM	NM
BAT-2I	0.87	NA	0.67	NM	NM	3.06	27.88	NA	29.51	23.93	NM	28.29
BAT-2D	0.87	NA	NA	NM	NM	NM	26.82	NA	27.92	25.84	NM	NM
BAT-3S	0.91	NA	NA	NA	NA	NA	26.44	NA	NA	NA	NA	NA
BAT-3I	0.70	NA	NA	NA	NA	0.28	26.56	NA	NA	NA	NA	26.69
BAT-3D	0.76	NA	NA	NA	NA	NA	26.29	NA	NA	NA	NA	NA
BAT-5S	0.43	0.71	1.73	NM	0.53	0.33	28.51	29.43	28.08	26.28	24.52	27.04
BAT-5I	0.52	NA	2.03	NM	NM	NM	27.40	NA	27.93	23.00	NM	NM
BAT-5D	0.64	NA	0.69	NM	0.87	0.74	27.62	NA	26.52	24.03	25.66	28.72
BAT-6S	0.50	NA	NA	NA	NA	NA	26.72	NA	NA	NA	NA	NA
BAT-6I	0.50	NA	NA	NA	NA	NA	27.30	NA	NA	NA	NA	NA
BAT-6D	0.41	NA	NA	NA	NA	NA	26.49	NA	NA	NA	NA	NA
PA-4S	0.49	NA	NA	NA	NA	NA	26.30	NA	NA	NA	NA	NA
PA-4I	0.59	NA	NA	NA	NA	NA	26.64	NA	NA	NA	NA	NA
PA-4D	0.30	NA	NA	NA	NA	NA	26.09	NA	NA	NA	NA	NA
<b>Oxidation Perimeter Wells</b>												
PA-3S	0.51	0.71	1.73	1.50	NM	NM	26.07	28.11	28.94	23.46	NM	NM
PA-3I	0.63	0.64	2.49	1.07	0.54	0.26	26.44	27.93	28.62	23.44	26.12	28.42
PA-3D	1.07	0.77	3.52	0.16	NM	NM	26.81	27.80	29.29	24.24	NM	NM
PA-5S	0.11	0.35	0.64	NA	0.37	NM	28.25	27.34	27.28	25.84	24.28	NM
PA-5I	1.85	0.43	0.72	NA	0.35	0.83	28.87	27.22	27.10	26.01	24.91	25.23
PA-5D	0.46	0.45	1.57	NA	0.57	0.82	27.02	26.86	26.89	25.76	25.70	25.89
PA-6S	0.87	0.40	0.70	0.22	0.22	0.73	28.22	27.49	27.24	25.08	23.01	25.05
PA-6I	0.66	0.45	0.76	0.16	0.25	1.09	28.45	27.27	26.60	25.62	23.95	25.58
PA-6D	0.70	0.54	1.57	NA	0.34	0.65	27.81	26.59	26.42	25.47	24.54	26.45
PA-9S	0.47	0.39	2.15	1.15	2.20	0.38	26.79	27.36	26.12	25.63	25.68	26.25
PA-9I	1.01	0.73	2.65	2.19	0.32	0.31	26.52	28.20	26.15	25.71	26.15	26.10
PA-9D	1.03	0.77	2.06	2.88	0.31	0.43	26.25	27.04	25.87	25.43	25.88	26.01
PA-12S	0.65	0.70	1.47	NA	0.28	0.50	25.67	26.26	26.48	27.13	25.35	26.34
PA-12I	0.59	0.76	1.96	NA	0.34	0.46	26.01	26.65	26.41	26.49	25.46	26.09
PA-12D	0.43	0.90	2.13	NA	0.41	0.57	25.99	25.97	26.19	25.79	25.31	26.23
<b>SPH Plot Wells</b>												
PA-13S	0.28	0.86	NA	NA	0.22	NA	26.12	43.74	NA	NA	43.71	NA
PA-13I	0.27	0.91	NA	NA	0.07	NA	27.36	30.93	NA	NA	31.12	NA
PA-13D	0.62	2.21	NA	NA	0.02	NA	27.26	44.51	NA	NA	40.86	NA
PA-14S	0.31	0.10	NA	NA	0.34	NA	26.94	30.29	NA	NA	53.97	NA
PA-14I	0.40	0.77	NA	NA	0.15	NA	27.70	39.99	NA	NA	38.29	NA
PA-14D	0.10	1.13	NA	NA	0.24	NA	27.29	43.32	NA	NA	37.70	NA
<b>SPH Perimeter Wells</b>												
PA-2S	0.84	0.42	NA	NA	0.46	0.34	27.00	27.45	NA	21.57	42.07	34.61
PA-2I	0.48	0.79	NA	NA	0.39	0.45	27.03	27.43	NA	24.66	26.68	32.22

**Table D-1. Groundwater Field Parameters (Continued)**

Well ID	DO (mg/L)						Temperature (°C)					
	Pre-Demo	Week 3-4	Week 7-8	Jan. 2000	Apr 2000	OX Post-Demo	Pre-Demo	Week 3-4	Week 7-8	Jan. 2000	Apr 2000	OX Post-Demo
PA-2D	0.80	0.29	NA	NA	0.36	0.68	26.36	27.80	NA	23.15	30.91	33.29
PA-7S	0.52	0.41	NA	NA	1.02	NA	28.84	28.60	NA	29.42	49.21	NA
PA-7I	0.43	0.58	NA	NA	1.46	NA	28.53	28.74	NA	26.77	36.14	NA
PA-7D	0.43	0.73	NA	NA	NA	NA	28.08	28.33	NA	28.29	39.63	NA
PA-10S	0.54	0.96	NA	NA	1.24	NA	23.67	36.77	NA	29.95	45.76	NA
PA-10I	0.54	0.76	NA	NA	0.85	NA	23.71	30.73	NA	32.16	32.95	NA
PA-10D	0.89	0.46	NA	NA	1.47	NA	23.76	29.88	NA	32.10	33.60	NA
IW-17S	0.46	2.46	NA	NA	Dry	NA	28.39	40.76	NA	44.32	Dry	NA
IW-17I	0.47	0.79	NA	NA	0.73	NA	27.01	29.37	NA	37.25	39.02	NA
IW-17D	0.34	0.81	NA	NA	0.34	NA	26.85	28.05	NA	30.45	40.30	NA
PA-15	NA	NA	NA	NA	0.27	NA	NA	NA	NA	36.75	32.57	NA
<b>Distant Wells</b>												
PA-1S	0.43	0.58	1.11	0.18	0.42	0.37	26.96	27.25	27.62	26.03	24.46	24.96
PA-1I	0.49	0.41	0.33	1.23	0.64	0.41	27.60	30.42	27.49	26.10	25.27	25.73
PA-1D	0.23	0.51	0.39	1.43	0.48	0.48	27.09	27.43	27.38	25.94	25.64	26.39
PA-8S	0.69	0.40	0.30	NA	0.47	0.38	28.91	28.74	27.97	25.55	24.96	26.32
PA-8I	0.68	0.87	0.51	NA	0.48	0.36	28.65	28.51	27.58	25.28	25.60	26.40
PA-8D	0.73	0.56	0.84	NA	0.55	0.68	27.67	27.78	27.43	25.15	25.76	26.13
PA-11S	0.47	0.54	0.67	NA	0.50	NM	24.82	25.58	26.15	25.45	24.83	NM
PA-11I	0.21	0.66	1.20	NA	0.52	0.56	25.29	25.87	26.01	25.14	24.75	25.80
PA-11D	0.54	1.09	2.38	NA	0.60	0.66	24.64	25.43	25.51	24.83	24.53	25.12

**Table D-1. Groundwater Field Parameters (Continued)**

Well ID	Eh (mV)						Conductivity (mS/cm)					
	Pre-Demo	Week 3-4	Week 7-8	Jan 2000	Apr 2000	OX Post-Demo	Pre-Demo	Week 3-4	Week 7-8	Jan 2000	Apr 2000	OX Post-Demo
<b>Oxidation Plot Wells</b>												
BAT-1S	80.3	NA	NA	NA	NA	0.790	NA	NA	NA	NA	NA	NA
BAT-II	54.6	NA	NA	NA	NA	1.383	NA	NA	NA	NA	NA	NA
BAT-1D	58.7	NA	NA	NA	NA	2.519	NA	NA	NA	NA	NA	NA
BAT-2S	81.7	776.5	668.8	367.4	NA	0.760	6.049	16.260	4.836	NM	NM	
BAT-2I	47.9	NA	593.1	368.1	NA	681.2	1.343	NA	14.340	5.012	NM	9.47
BAT-2D	53.4	NA	408.8	426.9	NA	NA	2.552	NA	3.852	12.170	NM	NM
BAT-3S	58.8	NA	NA	NA	NA	0.673	NA	NA	NA	NA	NA	NA
BAT-3I	43.9	NA	NA	NA	NA	200.3	1.360	NA	NA	NA	NA	10.03
BAT-3D	46.9	NA	NA	NA	NA	NA	2.626	NA	NA	NA	NA	NA
BAT-5S	48.3	369.8	531.9	388.3	203.5	295.0	0.520	1.759	2.869	1.034	6.60	6.65
BAT-5I	32.5	NA	447.5	442.2	NA	NA	0.679	NA	3.145	1.117	NM	NM
BAT-5D	66.1	NA	305.4	469.1	336.0	213.4	2.584	NA	3.609	3.720	11.86	14.62
BAT-6S	59.7	NA	NA	NA	NA	0.910	NA	NA	NA	NA	NA	NA
BAT-6I	36.4	NA	NA	NA	NA	NA	1.356	NA	NA	NA	NA	NA
BAT-6D	50.7	NA	NA	NA	NA	NA	2.684	NA	NA	NA	NA	NA
PA-4S	171.8	NA	NA	NA	NA	0.620	NA	NA	NA	NA	NA	NA
PA-4I	159.4	NA	NA	NA	NA	0.756	NA	NA	NA	NA	NA	NA
PA-4D	174.8	NA	NA	NA	NA	2.664	NA	NA	NA	NA	NA	NA
<b>Oxidation Perimeter Wells</b>												
PA-3S	162.1	109.1	346.5	397.2	NA	NA	0.655	1.264	5.043	1.823	NM	NM
PA-3I	169.3	146.0	238.4	450.0	-34.9	202.0	1.097	1.047	6.186	2.219	10.57	8.64
PA-3D	106.7	143.3	160.1	453.9	NA	NA	2.827	2.493	12.570	3.709	NM	NM
PA-5S	149.1	166.5	191.8	181.1	218.8	NA	0.512	0.448	1.079	1.883	144.60	NM
PA-5I	117.3	73.4	96.2	198.1	212.0	214.9	0.668	0.611	1.334	1.787	59.80	2.81
PA-5D	134.3	110.1	125.2	183.1	73.8	143.7	2.492	2.364	5.308	5.543	56.52	2.42
PA-6S	121.8	41.2	59.9	433.0	147.2	244.2	0.545	0.489	1.225	4.167	42.46	1.74
PA-6I	171.0	119.6	120.2	352.6	146.8	266.9	0.874	0.836	2.078	2.616	75.62	3.27
PA-6D	124.0	68.6	139.1	358.7	122.5	153.5	2.626	2.544	5.318	5.746	97.40	3.64
PA-9S	164.7	103.6	183.0	196.3	306.1	207.4	1.444	0.927	2.275	2.754	27.23	4.13
PA-9I	165.6	76.1	98.6	139.2	203.0	226.4	1.051	1.444	3.532	4.129	96.81	4.21
PA-9D	123.6	113.5	146.6	176.0	81.1	189.5	2.521	2.341	5.096	5.654	107.10	4.07
PA-12S	61.6	68.8	63.8	174.0	172.7	199.1	0.711	0.644	1.520	10.590	162.40	7.94
PA-12I	58.2	70.8	70.8	122.6	156.7	187.5	0.957	0.964	2.390	3.415	110.50	5.13
PA-12D	46.0	76.3	71.1	109.9	127.6	160.9	2.663	2.587	5.725	6.247	140.00	6.20
<b>SPH Plot Wells</b>												
PA-13S	89.1	113.3	NA	NA	10.9	NA	0.884	1.013	NA	NA	125.90	NA
PA-13I	123.1	50.2	NA	NA	214.5	NA	0.926	0.991	NA	NA	146.40	NA
PA-13D	91.2	125.6	NA	NA	185.4	NA	3.384	2.663	NA	NA	377.80	NA
PA-14S	67.4	0.7	NA	NA	89.0	NA	0.776	1.187	NA	NA	251.60	NA
PA-14I	78.7	45.1	NA	NA	36.9	NA	1.171	4.457	NA	NA	272.50	NA
PA-14D	55.3	138.5	NA	NA	66.0	NA	2.836	2.771	NA	NA	224.40	NA
<b>SPH Perimeter Wells</b>												
PA-2S	138.7	58.5	NA	199.4	19.3	143.9	0.669	0.579	NA	2.762	84.69	3.33
PA-2I	165.1	128.1	NA	170.0	194.4	162.3	0.900	1.439	NA	1.723	93.10	3.09

**Table D-1. Groundwater Field Parameters (Continued)**

Well ID	Eh (mV)						Conductivity (mS/cm)					
	Pre-Demo	Week 3-4	Week 7-8	Jan 2000	Apr 2000	OX Post-Demo	Pre-Demo	Week 3-4	Week 7-8	Jan 2000	Apr 2000	OX Post-Demo
PA-2D	107.2	33.4	NA	165.0	221.3	184.4	3.108	0.663	NA	4.294	146.60	5.48
PA-7S	114.5	85.8	NA	175.4	140.0	NA	0.854	0.932	NA	1.678	48.07	NA
PA-7I	163.1	116.7	NA	176.6	207.6	NA	1.704	1.335	NA	1.887	60.81	NA
PA-7D	140.9	53.0	NA	169.1	238.7	NA	2.562	1.840	NA	3.060	39.63	NA
PA-10S	77.5	97.8	NA	154.2	175.1	NA	0.804	0.817	NA	3.245	66.59	NA
PA-10I	67.3	97.2	NA	164.6	171.8	NA	0.953	0.893	NA	1.980	48.10	NA
PA-10D	65.9	243.2	NA	171.6	207.6	NA	3.125	1.414	NA	6.474	121.90	NA
IW-17S	184.6	167.5	NA	174.7	NA	NA	0.783	1.333	NA	2.475	Dry	NA
IW-17I	184.7	100.4	NA	164.5	220.1	NA	2.202	0.835	NA	2.160	111.90	NA
IW-17D	81.2	-45.3	NA	152.5	211.3	NA	2.607	2.197	NA	5.720	116.30	NA
PA-15	NA	NA	NA	142.9	106.6	NA	NA	NA	NA	4.041	76.05	NA
<b>Distant Wells</b>												
PA-1S	139.6	198.6	345.2	340.4	242.0	NA	0.355	0.389	1.221	1.375	1.26	1.39
PA-1I	183.7	177.5	251.8	202.4	300.1	231.7	0.676	0.450	0.860	1.861	1.93	1.73
PA-1D	84.8	183.6	-565.4	172.2	230.2	206.9	2.225	1.347	4.449	5.392	4.76	4.79
PA-8S	100.8	135.2	81.1	506.6	263.6	238.6	0.746	0.666	1.373	5.615	4.92	5.11
PA-8I	190.4	201.3	165.2	406.5	197.8	182.2	1.043	1.029	2.688	3.572	3.92	3.81
PA-8D	178	206.0	146.3	384.0	173.2	244.2	2.600	2.328	5.216	5.752	7.53	7.22
PA-11S	72.2	119.2	121.0	144.9	225.7	NA	0.829	0.737	1.534	1.517	187.20	NM
PA-11I	60.6	103.1	63.5	169.8	211.0	221.1	0.878	0.750	1.773	1.848	67.76	11.92
PA-11D	60.7	123.8	100.3	140.6	153.1	163.7	2.881	2.474	5.635	6.103	121.60	5.52

NA: Not available.

NM: Not measureable.

**Table D-2. Iron and Manganese Results of Groundwater Samples**

Compound	Iron (mg/L)							Manganese (mg/L)						
SMCL	0.3 mg/L							0.05 mg/L						
Well ID	Pre-Demo	Week 3-4	Week 7-8	Jan 2000	Apr 2000	OX Post-Demo	Pre-Demo	Week 3-4	Week 7-8	Jan 2000	Apr 2000	OX Post-Demo		
<b>Oxidation Plot Wells</b>														
BAT-2S	0.26	<0.05	<1.2	<0.050	<0.05	<0.1	0.016							
BAT-2I		NA	<0.05	<0.050	<0.05	<0.1	0.018	NA						
BAT-2I-DUP	NA	NA	<0.05	<0.050	NA	NA	NA	NA				NA	NA	
BAT-2D	0.12	NA	0.11	0.16	NS <sup>1</sup>	<0.05	0.015	NA				NS <sup>1</sup>		
BAT-5S		0.74		<0.050	0.15	<0.05						<0.015		
BAT-5I	<0.05	NA		<0.050	<0.05	<0.1	<0.015	NA						
BAT-5D		NA		0.14	<0.05		0.025	NA						
BAT-5D-DUP	NA	NA		NA	<0.05		NA	NA				NA		
<b>Oxidation Perimeter Wells</b>														
PA-3S		<0.05	<0.050	<0.05	<0.1			0.047						
PA-3S-DUP	NA	NA	NA	NA	NA	<0.1	NA	NA	NA	NA	NA	NA		
PA-3I	0.1				0.24		0.018	0.022						
PA-3I-DUP	NA	0.23	NA	NA	NA	NA	NA	0.015	NA	NA	NA	NA		
PA-3D	0.2	0.18		<0.050	<0.05	<0.25								
PA-3D-DUP	NA	NA	NA	<0.050	NA	NA	NA	NA	NA	NA	NA	NA		
PA-5S						0.18	0.026	0.022	0.03	0.047				
PA-5I								0.043	0.04	0.028				
PA-5D	<0.05	0.18	<0.05	0.09	<0.05	<0.05	0.024	0.023	<0.015	0.017	0.016	0.032		
PA-6S				0.5	<0.05	0.05	0.027	0.030	0.036	0.019	<0.015	<0.015		
PA-6I	<0.05		0.18	0.14	<0.05	<0.05	0.022	0.019	<0.015	0.015	<0.015	0.024		
PA-6D	0.13	0.27	0.13	0.13	<0.05			0.024	0.015	0.015	<0.015			
PA-9S	<0.05				<0.05		0.026	0.031	0.025	0.023	0.023			
PA-9S-DUP	NA	NA	NA	NA	<0.05	NA	NA	NA	NA	NA	NA	0.022	NA	
PA-9I	0.092				0.29	<0.05	<0.05	0.031	0.027	0.027	0.024	0.015		
PA-9D	0.24	0.097	0.051	<0.050	<0.05	<0.05	0.034	0.022	0.015	0.016	<0.015	0.015		
PA-12S									0.044		0.12			
PA-12I							0.047	0.027	0.02	<0.015				
PA-12D								0.048	0.03					
<b>SPH Plot Wells</b>														
PA-13S		NA	NA	NA	0.24	NA		NA	NA	NA	0.038	NA		
PA-13I		NA	NA	NA		NA	0.023	NA	NA	NA				
PA-13D	<0.05	NA	NA	NA		NA	<0.015	NA	NA	NA	<0.015	NA		
PA-14S		NA	NA	NA		NA	0.022	NA	NA	NA	0.015	NA		
PA-14I		NA	NA	NA		NA		NA	NA	NA				
PA-14D		NA	NA	NA		NA	0.02	NA	NA	NA	0.028	NA		
<b>SPH Plot Perimeter Wells</b>														
PA-2S			NA						NA					
PA-2I	0.28		NA				0.03		NA			0.048		
PA-2I-DUP	NA	NA	NA	NA		NA	NA	NA	NA	NA		NA		
PA-2D			NA						NA	0.033		0.036		
PA-7S			NA				NA	0.037		NA		NA		
PA-7I	<0.05	<0.05	NA	0.26		NA	0.03	0.026	NA	0.02		NA		
PA-7D	<0.05		NA		0.24	NA	0.028	0.039	NA	0.03		NA		

**Table D-2. Iron and Manganese Results of Groundwater Samples (Continued)**

Compound	Iron (mg/L)						Manganese (mg/L)					
SMCL	0.3 mg/L						0.05 mg/L					
Well ID	Pre-Demo	Week 3-4	Week 7-8	Jan 2000	Apr 2000	OX Post-Demo	Pre-Demo	Week 3-4	Week 7-8	Jan 2000	Apr 2000	OX Post-Demo
PA-7D-Dup	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PA-10S			NA			NA		0.039	NA	0.044	0.047	NA
PA-10I			NA			NA			NA	0.12		NA
PA-10I-Dup	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PA-10D			NA			NA	0.029		NA	0.044	0.021	NA
PA-10D-DUP	NA	NA	NA		NA	NA	NA	NA	NA	0.044	NA	NA
IW-17S	0.16		NA	0.099	NS <sup>2</sup>	NA	0.035		NA	<0.015	NS <sup>2</sup>	NA
IW-17I	<0.05		NA			NA			NA			NA
IW-17D	0.24	NA	NA	<0.050	<0.05	NA		NA	NA	<0.015	0.024	NA
PA-15	NA	NA	NA	<0.050		NA	NA	NA	NA	<0.015		NA
<b>Steam Injection Plot Wells</b>												
PA-16S	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PA-16I	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PA-16D	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PA-17S	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PA-17I	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PA-17D	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PA-17D-Dup	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
<b>Distant Wells</b>												
PA-1S	0.12	<0.05	<0.05		0.2		<0.015	<0.015	<0.015	0.039	0.015	0.019
PA-1I	<0.05	<0.05	<0.05	0.082	<0.05	<0.05	<0.015	<0.015	<0.015	<0.015	0.018	0.017
PA-1I-DUP	NA	NA	NA	NA	NA	<0.05	NA	NA	NA	NA	NA	0.019
PA-1D	0.11	0.12	0.16	0.15	<0.05	<0.05	0.037	0.040	0.037	0.026	0.021	0.021
PA-1D-Dup	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PA-8S				0.16								
PA-8S-DUP	NA	NA			NA	NA	NA	NA		NA	NA	
PA-8I	0.23	0.14	<0.05				0.028	0.027	0.028			
PA-8D	<0.05	<0.05	<0.05				0.029	0.022	<0.015	0.045		
PA-8D-DUP	NA	<0.05	NA	NA	NA	NA	NA	0.026	NA	NA	NA	NA
PA-11S					<0.1		0.061		0.046			
PA-11I							0.028	0.034	0.043	0.028		
PA-11D							0.026	0.019	0.023	0.019	0.022	0.019

NA: Not available.

NS: Not sampled.

<: The compound was analyzed but not detected at or above the specified reporting limit.

SMCL: Secondary Maximum Contaminant Level.

\_\_\_\_\_ is that the concentration exceeds or equals to the SMCL.

1. Sample was not collected due to excess amount of KMnO<sub>4</sub> in the flush mount.

2. Sample was not collected because the well was dry.

**Table D-3. Chloride and Total Dissolved Solids Results of Groundwater Samples**

SMCL	Chloride (mg/L)							TDS (mg/L)						
	250 mg/L							500 mg/L						
Well ID	Pre-Demo	Week 3-4	Week 7-8	Jan 2000	Apr 2000	OX Post-Demo	Pre-Demo	Week 3-4	Week 7-8	Jan 2000	Apr 2000	OX Post-Demo		
<b>Oxidation Plot Wells</b>														
BAT-2S	52.5	<1,000	<1,000		228 J	237 J	499							
BAT-2I	181	NA		105		238		NA						
BAT-2I-DUP	NA	NA		125	NA	NA	NA	NA				NA	NA	
BAT-2D		NA	109		NS			NA				NS		
BAT-5S	37.5	101	141	77.8	234 J	236	387				361			
BAT-5S-DUP	NA	NA	NA	NA	NA	NA	402	NA	NA	NA	NA	NA	NA	
BAT-5I	57	NA		77				NA			329			
BAT-5I-DUP	NA	NA	NA	NA	NA	NA		NA	NA	NA	NA	NA	NA	
BAT-5D		NA						NA						
BAT-5D-DUP	NA	NA		NA			NA	NA			NA			
<b>Oxidation Perimeter Wells</b>														
PA-3S	30.2	119		88.4	146 J		398				475			
PA-3S-DUP	NA	NA	NA	NA	NA	153 J	NA	NA	NA	NA	NA			
PA-3I	114	121		86.4	110	156								
PA-3I-DUP	NA	121	NA	NA	NA	NA	NA		NA	NA	NA	NA	NA	
PA-3D				123					NA	NA				
PA-3D-DUP	NA	NA	NA		NA	NA	NA	NA	NA		NA	NA		
<b>Distant Wells</b>														
PA-1S	9.8	13.9	23	33.9	51.6	60.3	205	293	319	326	413	470		
PA-1I	66.2	44.3	32.5	92.6	122	105	424	313	277	442				
PA-1I-DUP	NA	NA	NA	NA	NA	111	NA	NA	NA	NA	NA			
PA-1D														
PA-1D-Dup	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
PA-8S	24.2	23.8	26.3					445	458	415				
PA-8S-DUP	NA	NA	26.9		NA	NA	NA	NA	NA	405		NA	NA	
PA-8I	119	130	182											
PA-8D														
PA-8D-DUP	NA	723	NA	NA	NA	NA	NA		NA	NA	NA	NA	NA	
PA-11S	36.7	28.3	28.9	34.1										
PA-11I	49	44.2	46.7	48.5	248									
PA-11D														
PA-11D-DUP	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1,760

NA: Not available.

NS: Not sampled.

SMCL: Secondary Maximum Contaminant Level.

J: Estimated but below the detection limit.

Shading denotes that the concentration exceeds the SMCL Level.

**Table D-4. Potassium Results of Groundwater Samples**

Well ID	KMnO <sub>4</sub>	Mn	MnO <sub>4</sub>	KMnO <sub>4</sub>	Mn	MnO <sub>4</sub>	KMnO <sub>4</sub>	Mn	MnO <sub>4</sub>	KMnO <sub>4</sub>	Mn	MnO <sub>4</sub>	
	4/12 - 4/16	4/26 - 4/27		5/11 - 5/12		8/22 - 8/23		5/11 - 5/12		8/22 - 8/23		11/29 - 11/30	
<b>Oxidation Plot Wells</b>													
BAT-1S	NA	NA	7	3	6	>6,000	>2,000	NA	NA	NA	NA	NA	NA
BAT-1I	NA	NA	8	3	6	27	10	20	NA	NA	NA	NA	NA
BAT-1D	NA	NA	265	92	200	117	41	88	NA	NA	NA	NA	NA
BAT-2S	>6,000	>2,000	1,150	400	870	1,100	380	830	1,500	490	1,020	2,020	1,510
BAT-2I	NA	NA	1,260	440	950	250	90	190	340	120	220	8.8	3.8
BAT-2D	NA	NA	5	2	4	10	4	8	8	2	6	19.3	8.2
BAT-3S	NA	NA	448	156	337	159	55	120	NA	NA	NA	NA	NA
BAT-3I	NA	NA	4	1	3	19	7	14	NA	NA	NA	NA	NA
BAT-3D	NA	NA	5,050	1,760	3,800	2,490	870	1,880	NA	NA	NA	NA	NA
BAT-5S	3	1	2	9.0	3.0	7.0	1.3	0.5	1.0	0.8	0.3	0.6	5.5
BAT-5I	>6,000	>2,000	3,660	1,270	2,750	>6,000	>2,000	>6,000	>2,000	>6,000	>2,000	>6,000	>6,000
BAT-5D	3	1	2	30	10	22	3	1	2	1.9	0.8	1.5	2.1
BAT-6S	NA	NA	280	100	210	200	70	150	NA	NA	NA	NA	NA
BAT-6I	NA	NA	470	160	350	77	27	58	NA	NA	NA	NA	NA
BAT-6D	NA	NA	195	65	145	650	230	490	NA	NA	NA	NA	NA
PA-4S	NA	NA	2780	970	2090	1,420	490	1,070	NA	NA	NA	NA	NA
PA-4I	NA	NA	670	230	510	1,940	670	1,460	NA	NA	NA	NA	NA
PA-4D	NA	NA	>6,000	>2,000	>6,000	5,490	1,910	4,130	NA	NA	NA	NA	NA
<b>Oldation Perimeter Wells</b>													
PA-3S	>6,000	>2,000	>6,000	>2,000	>6,000	>2,000	>6,000	>2,000	>6,000	>2,000	>6,000	>6,000	NA
PA-3I	>60	>20	9.0	3.0	7.0	90	31	68	75	22	54	NA	NA
PA-3D	>6,000	>2,000	>6,000	>2,000	>6,000	6,450	2,240	4,860	>6,000	>6,000	NA	NA	NA
PA-5S	35.4	12.3	26.7	42.6	14.8	32.1	5	2	4	NA	NA	NA	NA
PA-5I	0.4	0.1	0.3	1.0	0.4	0.8	20.0	7.0	15.0	NA	NA	NA	NA
PA-5D	0.1	0	0.1	1.4	0.5	1.1	1.0	1.0	NA	NA	NA	NA	NA
PA-6S	0.2	0.1	0.1	0.6	0.2	0.5	0.5	0.2	0.4	NA	NA	NA	NA
PA-6I	0.1	0	0.1	0.2	0.1	0.2	0.3	0.1	0.2	NA	NA	NA	NA
PA-6D	0.1	0	0.1	1.3	0.4	0.9	1.6	0.6	1.2	NA	NA	NA	NA
PA-9S	0.2	0.1	0.1	0.6	0.2	0.4	0.3	0.1	0.3	NA	NA	NA	NA
PA-9I	0.1	0	0.1	1.8	0.6	1.3	0.7	0.2	0.5	NA	NA	NA	NA
PA-9D	0.2	0.1	0.2	1.2	0.4	0.9	1.5	0.5	1.1	NA	NA	NA	NA

**Table D-4. Potassium Results of Groundwater Samples (Continued)**

Units (mg/L)	KMnO <sub>4</sub>	Mn	MnO <sub>4</sub>	KMnO <sub>4</sub>	Mn	MnO <sub>4</sub>	KMnO <sub>4</sub>	Mn	MnO <sub>4</sub>	KMnO <sub>4</sub>	Mn	MnO <sub>4</sub>	KMnO <sub>4</sub>	Mn	MnO <sub>4</sub>		
<b>Well ID</b>	<b>4/12 - 4/16</b>			<b>4/26 - 4/27</b>			<b>5/11 - 5/12</b>			<b>8/22 - 8/23</b>			<b>11/29 - 11/30</b>				
PA-12S	1.1	0.4	0.9	1.3	0.4	1.0	2.0	0.7	1.5	NA	NA	NA	NA	NA	NA	NA	
PA-12I	0.7	0.2	0.5	1.3	0.4	1.0	0.5	0.2	0.4	NA	NA	NA	NA	NA	NA	NA	
PA-12D	3.8	1.3	2.9	>60	>20	>60	44.0	15.0	33.0	NA	NA	NA	NA	NA	NA	NA	
<b>SPH Perimeter Wells</b>																	
PA-2S	NA	NA	NA	NA	NA	NA	NA	0.5	0.2	0.4	0.3	0.1	0.1	NA	NA	NA	
PA-2I	NA	NA	NA	NA	NA	NA	NA	1.2	0.4	0.9	0.3	0.1	0.2	NA	NA	NA	
PA-2L-DUP	NA	NA	NA	NA	NA	NA	NA	8.9	3.1	6.7	0.4	0.2	0.2	NA	NA	NA	
<b>Distant Wells</b>																	
PA-1S	NA	NA	NA	NA	NA	NA	NA	0.4	0.2	0.3	0.4	0.2	0.2	0.3	NA	NA	
PA-1I	NA	NA	NA	NA	NA	NA	NA	0.5	0.2	0.4	0.5	0.2	0.4	NA	NA	NA	
PA-1D	NA	NA	NA	NA	NA	NA	NA	1.2	0.4	0.9	1.2	0.4	0.9	NA	NA	NA	
PA-8S	NA	NA	NA	NA	NA	NA	NA	6.8	2.4	5.1	NA	NA	NA	NA	NA	NA	
PA-8I	NA	NA	NA	NA	NA	NA	NA	1.9	0.7	1.5	NA	NA	NA	NA	NA	NA	
PA-8D	NA	NA	NA	NA	NA	NA	NA	1.3	0.5	1	NA	NA	NA	NA	NA	NA	
PA-11S	NA	NA	NA	NA	NA	NA	NA	1,280	450	970	NA	NA	NA	NA	NA	NA	
PA-11I	NA	NA	NA	NA	NA	NA	NA	17	6	12	NA	NA	NA	NA	NA	NA	
PA-11D	NA	NA	NA	NA	NA	NA	NA	2	1	1	NA	NA	NA	NA	NA	NA	
PA-16S	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.8	0.4	0.6	0.6	
PA-16I	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.4	0.2	0.3	0.3	
PA-16D	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.7	0.3	0.5	0.5	
PA-17S	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.5	0.2	0.4	0.4	
PA-17I	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.3	0.1	0.1	0.1	
PA-17D	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.4	0.2	0.2	0.2	

NA: Not available.

Purple bold face indicates that water sample was purple when collected.

**Table D-5. Trace Metal Results of Groundwater Samples**

Compound	Aluminum (mg/L)						Antimony (mg/L)					
	0.2 (Florida Secondary Standard)						0.006					
MCL	Pre-Demo	Week 3-4	Week 7-8	Jan 2000	Apr 2000	Post-Demo	Pre-Demo	Week 3-4	Week 7-8	Jan 2000	Apr 2000	Post-Demo
<b>Oxidation Plot Wells</b>												
BAT-2S	<0.2	<0.2	<5	<0.2	<0.2	<0.4	<0.006	<0.15	<0.006	<0.006	<0.006	<0.012
BAT-2I	<0.2	NA	<0.2	<0.2	<0.2	<0.4	<0.006	NA	<0.006	<0.006	<0.006	<0.012
BAT-2I-DUP	NA	NA	<0.2	<0.2	NA	<0.2	NA	NA	<0.006	<0.006	NA	<0.006
BAT-2D	<0.2	NA	<0.2	<0.2	NS	<0.2	<0.006	NA	<0.006	<0.006	NS	<0.006
BAT-5S	<0.2		<0.2	<0.2	<0.2	<0.4	<0.006	<0.006	<0.006	<0.006	<0.006	<0.012
BAT-5I	<0.2	NA	<0.2	<0.2	<0.2	<0.2	<0.006	NA	<0.006	<0.006	<0.006	<0.006
BAT-5D	<0.2	NA	<0.2	<0.2	<0.2	<0.2	<0.006	NA	<0.006	<0.006	<0.006	<0.006
BAT-5D-DUP	NA	NA	<0.2	NA	<0.2	NA	NA	NA	<0.006	<0.006	<0.006	<0.006
<b>Oxidation Perimeter Wells</b>												
PA-3S	<0.2	<0.2	<0.2	<0.2	<0.2	<0.4	<0.006	<0.006	<0.006	<0.006	<0.006	<0.012
PA-3S-DUP	NA	NA	NA	NA	NA	<0.4	NA	NA	NA	NA	NA	<0.012
PA-3I	<0.2	0.2	<0.2	<0.2	<0.2	<0.2	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
PA-3I-DUP	NA	<0.2	NA	NA	NA	NA	<0.006	NA	NA	NA	NA	NA
PA-3D	<0.2	<0.2	<0.2	<0.2	<0.2	<0.4	<0.006	<0.006	<0.006	<0.006	<0.006	<0.03
PA-3D-DUP	NA	NA	<0.2	NA	NA	NA	NA	NA	NA	NA	NA	NA
PA-5S	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
PA-5I	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
PA-5D	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
PA-6S	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
PA-6I	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
PA-6D	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
PA-9S	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
PA-9S-DUP	NA	NA	NA	NA	<0.2	NA	NA	NA	NA	NA	NA	<0.006
PA-9I	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
PA-9D	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
PA-12S	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
PA-12I	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
PA-12D	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
<b>Distant Wells</b>												
PA-11S	NA	NA	NA	NA	NA	<0.4	NA	NA	NA	NA	NA	<0.012
PA-11I	NA	NA	NA	NA	NA	<0.2	NA	NA	NA	NA	NA	<0.006
PA-11D	NA	NA	NA	NA	NA	<0.2	NA	NA	NA	NA	NA	<0.006

**Table D-5. Trace Metal Results of Groundwater Samples (Continued)**

Compound	MCL	Arsenic (mg/L)						Barium (mg/L)					
		Well ID	Pre-Demo	Week 3-4	Week 7-8	Jan 2000	Apr 2000	Post-Demo	Pre-Demo	Week 3-4	Week 7-8	Jan 2000	Apr 2000
<b>Oxidation Plot Wells</b>													
BAT-2S	<0.005	<0.005	<0.12	0.0068	<0.005	<0.01	<0.1	<0.1	<2.5	<0.1	<0.1	<0.1	<0.2
BAT-2I	<0.005	NA	0.0084	0.0058	<0.005	<0.01	NA	<0.1	NA	<0.1	<0.1	<0.1	<0.2
BAT-2I-DUP	NA	NA	0.0075	0.0062	NA	<0.005	NA	NA	<0.1	<0.1	NA	NA	<0.1
BAT-2D	<0.005	NA	<0.005	<0.005	NS	0.021	<0.1	NA	<0.1	<0.1	NS	<0.1	<0.1
BAT-5S	0.014	0.0061	0.0063	<0.005	<0.01	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.2
BAT-5I	<0.005	NA	<0.005	0.0058	0.013	0.0078	<0.1	NA	<0.1	<0.1	<0.1	<0.1	<0.1
BAT-5D	<0.005	NA	<0.005	<0.005	0.0055	0.0056	<0.1	NA	<0.1	<0.1	<0.1	<0.1	<0.1
BAT-5D-DUP	NA	NA	<0.005	NA	<0.005	NA	NA	NA	NA	NA	NA	<0.1	NA
<b>Oxidation Perimeter Wells</b>													
PA-3S	0.0058	0.0074	<0.005	<0.005	<0.005	<0.01	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.2
PA-3S-DUP	NA	NA	NA	NA	NA	<0.01	NA	NA	NA	NA	NA	NA	<0.2
PA-3I	<0.005	<0.005	0.0072	0.0062	0.018	0.018	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
PA-3I-DUP	NA	<0.005	NA	NA	NA	NA	NA	<0.1	NA	NA	NA	NA	NA
PA-3D	<0.005	<0.005	0.028	0.0055	<0.005	<0.025	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.2
PA-3D-DUP	NA	NA	<0.005	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PA-5S	0.0053	<0.005	0.0078	0.016	0.0055	<0.005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
PA-5I	0.0092	0.0052	0.0085	0.0087	<0.005	0.0078	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
PA-5D	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
PA-6S	0.0066	<0.005	0.0054	0.0079	<0.005	<0.005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
PA-6I	<0.005	<0.005	<0.005	0.0068	<0.005	<0.005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
PA-6D	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
PA-9S	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
PA-9S-DUP	NA	NA	NA	<0.005	NA	NA	NA	NA	NA	NA	NA	NA	NA
PA-9I	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
PA-9D	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
PA-12S	0.0072	0.0074	0.011	0.018	0.01	0.017	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
PA-12I	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
PA-12D	<0.005	<0.005	<0.005	<0.005	<0.005	0.0069	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
<b>Distant Wells</b>													
PA-11S	NA	NA	NA	NA	NA	<0.01	NA	NA	NA	NA	NA	NA	<0.2
PA-11I	NA	NA	NA	NA	NA	0.019	NA	NA	NA	NA	NA	NA	<0.1
PA-11D	NA	NA	NA	NA	NA	0.0059	NA	NA	NA	NA	NA	NA	<0.1

**Table D-5. Trace Metal Results of Groundwater Samples (Continued)**

Compound	MCL	Beryllium (mg/L)						Chromium (mg/L)					
		0.004			0.1			0.005			0.032		
Well ID	Pre-Demo	Week 3-4	Week 7-8	Jan 2000	Apr 2000	Post-Demo	Pre-Demo	Week 3-4	Week 7-8	Jan 2000	Apr 2000	Post-Demo	
<b>Oxidation Plot Wells</b>													
BAT-2S	<0.005	<0.005	<0.12	<0.005	<0.005	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.027	0.032
BAT-2I	<0.005	NA	<0.005	<0.005	<0.005	<0.01	<0.01	NA	NA	NA	NA	0.026	NA
BAT-2I-DUP	NA	NA	<0.005	<0.005	NA	<0.005	NA	NA	NA	NA	NA	NS	<0.005
BAT-2D	<0.005	NA	<0.005	<0.005	NS	<0.005	<0.01	NA	NA	NA	NA	NA	NA
BAT-5S	<0.005	<0.005	<0.005	<0.005	<0.005	<0.01	<0.005	<0.005	0.011	<0.005	<0.005	0.011	0.012
BAT-5I	<0.005	NA	<0.005	<0.005	<0.005	<0.005	<0.005	NA	0.019	<0.005	<0.005	<0.005	0.013
BAT-5D	<0.1	NA	<0.005	<0.005	<0.005	<0.005	<0.01	NA	<0.005	<0.005	<0.005	<0.005	0.013
BAT-5D-DUP	NA	NA	<0.005	NA	<0.005	NA	NA	NA	<0.005	NA	<0.005	NA	NA
<b>Oxidation Perimeter Wells</b>													
PA-3S	<0.005	<0.005	<0.005	<0.005	<0.005	<0.01	<0.01	<0.01	<0.005	<0.01	<0.01	<0.005	0.09
PA-3S-DUP	NA	NA	NA	NA	NA	<0.01	NA	NA	NA	NA	NA	NA	NA
PA-3I	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.01	0.041	<0.005	0.011	0.026	0.055
PA-3I-DUP	NA	<0.005	NA	NA	NA	NA	NA	NA	0.01	NA	NA	NA	NA
PA-3D	<0.005	<0.005	<0.005	<0.005	<0.005	<0.01	0.013	0.0067	0.033	<0.005	0.005	0.005	NA
PA-3D-DUP	NA	NA	<0.005	NA	NA	NA	NA	NA	NA	NA	<0.005	NA	NA
PA-5S	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.01	0.0054	<0.005	<0.005	<0.005	0.0058	NA
PA-5I	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.01	0.005	<0.005	<0.005	<0.005	<0.005	0.005
PA-5D	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.01	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
PA-6S	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.01	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
PA-6I	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.01	0.0093	<0.005	<0.005	<0.005	<0.005	<0.005
PA-6D	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.01	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
PA-9S	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
PA-9S-DUP	NA	NA	NA	NA	<0.005	NA	NA	NA	NA	NA	NA	NA	NA
PA-9I	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
PA-9D	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
PA-12S	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.01	<0.005	0.0057	<0.01	0.012	0.022	0.022
PA-12I	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.01	<0.005	<0.005	<0.005	0.01	<0.005	<0.005
PA-12D	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.01	<0.005	<0.005	<0.005	<0.005	0.043	0.043
<b>Distant Wells</b>													
PA-11S	NA	NA	NA	NA	NA	<0.01	NA	NA	NA	NA	NA	NA	NA
PA-11I	NA	NA	NA	NA	<0.005	NA	NA	NA	NA	NA	NA	<0.01	NA
PA-11D	NA	NA	NA	NA	<0.005	NA	NA	NA	NA	NA	NA	<0.005	NA

**Table D-5. Trace Metal Results of Groundwater Samples (Continued)**

Compound	MCL	Copper (mg/L)				Lead (mg/L)							
		Well ID	Pre-Demo	Week 3-4	Week 7-8	Jan 2000	Apr 2000	Post-Demo	Pre-Demo	Week 3-4	Week 7-8	Jan 2000	Apr 2000
<b>Oxidation Plot Wells</b>													
BAT-2S	<0.025	<0.025	<0.62	<0.025	0.05	<0.05	<0.003	<0.15	<0.075	<0.003	<0.09	<0.09	<0.06
BAT-2I	<0.025	NA	<0.025	<0.025	<0.025	<0.05	<0.003	NA	<0.003	<0.003	<0.09	<0.09	<0.015
BAT-2I-DUP	NA	NA	<0.025	<0.025	NA	<0.025	NA	NA	<0.003	<0.003	NA	NA	0.0046
BAT-2D	<0.025	NA	<0.025	<0.025	NS	<0.025	<0.003	NA	<0.003	<0.003	NS	NS	<0.003
BAT-5S	<0.025	<0.025	<0.025	<0.025	<0.05	<0.003	<0.003	<0.003	<0.003	<0.003	<0.09	<0.09	<0.09
BAT-5I	<0.025	NA	<0.025	<0.025	<0.025	<0.025	<0.003	NA	<0.003	<0.003	<0.003	<0.003	<0.003
BAT-5D	<0.025	NA	<0.025	<0.025	<0.025	<0.025	<0.003	NA	<0.003	<0.003	<0.003	0.0034	0.0034
BAT-5D-DUP	NA	NA	<0.025	NA	<0.025	NA	NA	NA	<0.003	NA	<0.003	NA	<0.003
<b>Oxidation Perimeter Wells</b>													
PA-3S	<0.025	<0.025	<0.025	<0.025	<0.025	<0.05	<0.003	<0.003	<0.006	<0.003	<0.003	<0.06	<0.09
PA-3S-DUP	NA	NA	NA	NA	NA	<0.05	NA	NA	NA	NA	NA	NA	<0.09
PA-3I	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
PA-3I-DUP	NA	<0.025	NA	NA	NA	NA	<0.003	NA	NA	NA	NA	NA	NA
PA-3D	<0.025	<0.025	<0.025	<0.025	<0.05	<0.003	<0.003	<0.003	<0.003	<0.003	<0.09	<0.09	<0.09
PA-3D-DUP	NA	NA	<0.025	NA	NA	NA	NA	NA	NA	<0.003	NA	NA	NA
PA-5S	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.003	<0.003	<0.003	<0.003	<0.003	<0.009	<0.009
PA-5I	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
PA-5D	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
PA-6S	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
PA-6I	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
PA-6D	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
PA-9S	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
PA-9S-DUP	NA	NA	<0.025	NA	NA	<0.025	NA	NA	NA	NA	NA	NA	NA
PA-9I	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
PA-9D	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
PA-12S	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.003	<0.003	<0.003	0.011	<0.003	<0.003	<0.003
PA-12I	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
PA-12D	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
<b>Distant Wells</b>													
PA-11S	NA	NA	NA	NA	NA	<0.05	NA	NA	NA	NA	NA	NA	<0.06
PA-11I	NA	NA	NA	NA	NA	<0.025	NA	NA	NA	NA	NA	NA	0.012
PA-11D	NA	NA	NA	NA	NA	<0.025	NA	NA	NA	NA	NA	NA	<0.003

**Table D-6. Other Parameter Results of Groundwater Samples**

Well ID	Ca (mg/L)		Mg (mg/L)		Na (mg/L)		Alkalinity (mg/L)	
	Pre-Demo	OX Post-Demo	Pre-Demo	OX Post-Demo	Pre-Demo	OX Post-Demo	Pre-Demo	OX Post-Demo
<b>Oxidation Plot Wells</b>								
BAT-2S	70.3	3.5	53.3	2.1	28.2	68.2	316	1,500
BAT-2I	41.2	3.8	58.5	3	164.0	74	323	1,280
BAT-2D	87.5	349	84.4	53	305.0	91	208	1,300
BAT-5S	NA	70.1	NA	111	NA	125	269	1,060
BAT-5I	NA	48.5	NA	19.4	NA	73	291	1,280
BAT-5D	84.0	210	81.5	203	311.0	125	204	2,140
BAT-5D-DUP	NA	214	NA	203	NA	124	NA	2,070

Well ID	NO <sub>3</sub> -NO <sub>2</sub> (mg/L)		SO <sub>4</sub> (mg/L)		BOD (mg/L)		TOC (mg/L)	
	Pre-Demo	OX Post-Demo	Pre-Demo	OX Post-Demo	Pre-Demo	OX Post-Demo	Pre-Demo	OX Post-Demo
<b>Oxidation Plot Wells</b>								
BAT-2S	<0.1	NA	46.0	<1,000	<3.0	<3.0	6.1	422
BAT-2I	<0.1	NA	138	NA	16	<3.0	15.5	86
BAT-2D	<0.1	1	103	379	13	16	10.2	10
BAT-5S	<0.1	<0.1	28.7	483	<3.0	112	4.2	157
BAT-5I	<0.1	NA	49.7	1,380	<3.0	<3.0	5.8	2,110
BAT-5D	<0.1	1	67.9	535	13	108	10.5	131
BAT-5D-DUP	NA	1	NA	529	NA	98	NA	129

NA: Not available.

BOD: Biological oxygen demand.

TOC: Total organic carbon.

1. NO<sub>3</sub>-NO<sub>2</sub> as nitrogen for BAT-2S/I and BAT-5I could not be analyzed due to abundant KMnO<sub>4</sub>. Also, BOD showed no depletion because of the oxidized nature of the matrix.

**Table D-7. TOC Results of Soil Samples**

Pre-Demo			Post-Demo		
Sample ID	SW9060 (mg/kg)	Walkley- Black (mg/kg)	Sample ID	SW9060 (mg/kg)	Walkley- Black (mg/kg)
<i>Oxidation Plot</i>					
SB-17-22	NA	<2,000	SB-216-16	9,840	<100
SB-17-34	NA	<2,000	SB-216-26	7,820	<100
SB-17-42	NA	2,200	SB-216-38	25,400	<100
SB-18-16	NA	<2,000	SB-221-16	14,800	<100
SB-18-28	NA	<2,000	SB-221-26	11,400	<100
SB-18-36	NA	<2,000	SB-221-38	30,800	<100
<i>Steam Plot</i>					
SB-32-30	9,450	1,180	NA	NA	NA
SB-32-46	17,700	576	NA	NA	NA

Pre-Demo TOC samples in oxidation plot were processed using Walkley-Black methodology.

<: Result was not detected at or above the stated reporting limit.

NA: Not available.

## **Appendix E. Microbiological Assessment**

E.1 Microbiological Evaluation Work Plan

E.2 Work Plan for Biological Soil and Groundwater Sampling and Procedure

E.3 Microbiological Evaluation Test Results

Table E-1. Analysis of Soil Samples for Microbiological Parameters

Table E-2. Analysis of Groundwater Samples for Microbiological Parameters

## **E.1 Microbiological Evaluation Work Plan**

### **Biological Sampling & Analysis Work Plan**

#### ***The Effect of Source Remediation Methods on the Presence and Activity of Indigenous Subsurface Bacteria at Launch Complex 34, Cape Canaveral Air Station, Florida***

**Prepared by  
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June 28, 1999**

**(Modified by T. C. Hazen, LBNL; G. Sewell, EPA;  
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### **1.0 Purpose and Objectives**

Overall purpose is to evaluate effects of three DNAPL source remediation treatments on the indigenous bacterial population. The three treatments in three different plots at LC34 are six-phase heating (SPH), chemical oxidation (OX), and steam injection (SI). The objectives of the biological sampling and analysis are:

1. To determine the immediate effect that each remediation technology has on the microbial community structure and specifically on TCE biodegraders.
2. To establish how quickly the microbial communities at the site recover and if any of the effects could be long-term.
3. To determine at what point that biodegradation could be used to complete remediation of the plume.
4. To establish if any of the technologies could cause a short-term effect on significant biogeochemical processes and the distribution and abundance of potential pathogens in the environment.

### **2.0 Background**

Launch Pad 34 at Cape Canaveral Air Station has dense non-aqueous phase (DNAPL) concentrations of TCE over a wide aerial extent in relatively sandy soils with a shallow groundwater table (Resource Conservation and Recovery Act Facility Investigation Work Plan for Launch Complex 34, Cape Canaveral Air Station, Brevard County, Florida, 1996, Kennedy Space Center Report KSC-JJ-4277.). These conditions have made it an ideal site for side-by-side comparison of various DNAPL remediation technologies currently being conducted by the DNAPL Remediation Multi-agency Consortium. Initial sampling at the site revealed that there are also high concentrations of vinyl chloride and dichloroethylene indicating natural attenuation via biodegradation of the TCE plume has been occurring. Since these compounds are daughter products of the anaerobic reductive dechlorination of TCE by microbes (see discussion below) it is probable that these conditions could be greatly effected by the source remediation processes being tested. Since most of these processes will introduce air into the subsurface and are potentially toxic to many microbes they could have a variety of effects on the biological activity and biodegradation rates of contaminants in the source area and the surrounding plume. The effects could range from long-term disruption of the microbial community structure and biological activity at the site,

to a significant stimulation of biodegradation of TCE. Whatever the effect, it needs to be monitored carefully since the long-term remediation of this or any similar site will be significantly effected not only by the technologies ability to remove the DNAPL source but also by the rate of biodegradation both natural and stimulated that can occur in the aquifer after the source is removed. The rate and extent of biodegradation will effect how low the technology must lower the source concentration before natural or stimulated bioremediation can complete the remediation to the ppb levels normally used as cleanup goals. It could also have a major effect on the life-cycle costs of remediation of these sites.

Secondarily, unlikely as this is, it is also important to verify that these source remediation technologies do not cause any gross changes biogeochemistry, and distribution and abundance of potential pathogens. The pathogens are a possibility at this site since there was long-term sewage discharge at the edge of test plots. Studies at other sites have suggested that stimulation of pathogens especially by thermal increases could be a possibility and thus should be considered in the overall risk scenario for these remediation technologies.

#### *Reductive Dechlorination of Chlorinated Solvents*

Microbial degradation of chlorinated solvents has been shown to occur under both anaerobic and aerobic conditions. Highly chlorinated solvents are in a relatively oxidized state and are hence more readily degraded under anaerobic conditions than under aerobic conditions (Vogel et al., 1987). In subsurface environments where oxygen is not always available, reductive dechlorination is one of most important naturally occurring biotransformation reactions for chlorinated solvents. Microbial reductive dechlorination is a redox reaction that requires the presence of a suitable electron donor to provide electrons for dechlorination of chlorinated organic (Freedman and Gossett, 1989).

Highly chlorinated solvents, such as tetrachloroethylene (PCE) and trichloroethylene (TCE), are commonly detected in the subsurface. Under anaerobic conditions, PCE is reductively dechlorinated to TCE, which in turn may be dechlorinated to 1,2-dichloroethylene (cis-1,2-DCE, or trans-1,2-DCE), followed sequentially by vinyl chloride (VC) and finally ethylene (Freedman and Gossett, 1989) or ethane (DeBruin et al. 1992). Further reductive dechlorination of DCE and VC to CO<sub>2</sub> and complete dechlorination of PCE to CO<sub>2</sub> are possible under anaerobic conditions (Bradley and Chapelle, 1996; Bradley and Chapelle, 1997; Bradley et al., 1998; Cabirol et al., 1998). However, complete dechlorination of PCE is often not achieved due to slow dechlorination process of its reduced intermediates, cis-1,2-DCE and VC, resulting the accumulation of these unfavorable intermediates in anaerobic environments. The accumulation of cis-1,2-DCE and VC is of great concern because they are known carcinogens. Such incomplete dechlorination is commonly observed in fields where reductive dechlorination of PCE and TCE is taking place (McCarty, 1996).

Reductive dechlorination reactions can be carried out by anaerobic microorganisms via either energy yielding or cometabolic processes. The energy-yielding process involves the use of chlorinated solvents as terminal electron acceptors (sometimes referred to as dehalorespiration). Anaerobic cultures that are capable of using PCE or TCE as terminal electron acceptors include the obligate anaerobes *Dehalospirillum multivorans* (Scholz-Muramatsu et al., 1995), *Dehalococcoides ethenogenes* (Maymo-Gattel et al., 1997), *Desulfitobacterium sp.* strain PCE1 (Gerritse et al ., 1996), *Desulfitobacterium sp.* strain PCE-S (Miller et al., 1997; Miller et al., 1998), *Desulfomonile tiedjei* (Fathepure et al., 1987; DeWeerd et al., 1990), *Dehalobacter restrictus* (Holliger and Schumacher, 1994; Holliger et al., 1998), strain TT4B (Krumholz et al., 1996), and the facultative organism strain MS-1 (Sharma and McCarty, 1996). With the exception of *Dehalococcoides ethenogenes* which dechlorinates PCE to ethene, and *Desulfitobacterium sp.* strain PCE1 which dechlorinates PCE to TCE, the end product of PCE dechlorination for all described pure cultures is cis-1,2, DCE. The end products of reductive dechlorination reactions vary depending on the physiological groups of bacteria involved. In acetogens, methanogens, and some other anaerobic bacteria, reductive dechlorination is believed to be mediated by metalloenzymes like the cobalt containing vitamin B12 and related corrinooids, and by the nickel containing cofactor F430. These metalloenzymes are present as components of enzymes that catalyze normal physiological pathways in several anaerobic bacteria, and fortuitously are able to reductively

dechlorinate several chlorinated compounds. Acetogenic and methanogenic bacteria contain high levels of these metallocoenzymes, the concentrations of which can be strongly dependent on growth substrates (Deikert et al., 1981; Krzycki and Zeikus, 1980).

The presence of a suitable electron donor, such as hydrogen or reduced organic compounds including hydrocarbons, natural organic matter, glucose, sucrose, propionate, benzoate, lactate, butyrate, ethanol, methanol, and acetate have been reported serve as electron donors for reductive dechlorination (Bouwer and McCarty, 1983; Carr and Hughes, 1998; DiStefano et al., 1992; Fennell and Gossett, 1997; Freedman and Gossett, 1989; Gibson and Sewell, 1992; Holliger et al., 1993; Lee et al., 1997; Tandoi et al., 1994). However, since the microbial populations differ from site to site and their responses to substrates vary greatly, the addition of certain types of electron donors may or may not effectively enhance reductive dechlorination processes. Both laboratory studies and field observations suggest that the addition of electron donors for the enhancement of dechlorination can induce complex scenarios that are a function of the subsurface conditions (Carr and Hughes, 1998; Fennell and Gossett, 1997) and the indigenous microbial population (Gibson and Sewell, 1992). Although it is known that hydrogen serves as the specific electron donor for reductive dechlorination (Holliger et al., 1993; Holliger and Schumacher, 1994; Maymo-Gatell et al., 1995), different concentrations of hydrogen stimulate different groups of anaerobic microbial populations which may or may not be responsible for dechlorination, and may out compete the halo respirers, making the direct addition of hydrogen problematic. In fact, recent research has indicated that dechlorinating bacteria possess lower half-velocity coefficients for H<sub>2</sub> utilization than methanogens, suggesting that dechlorinating bacteria should out compete methanogens at low H<sub>2</sub> concentrations (Ballapragada et al., 1997; Smatlak et al., 1996). In short-term microcosm studies, the addition of slow-release H<sub>2</sub> donors butyrate and propionate was found to support complete dechlorination as well as to enrich PCE-degrading bacteria (Fennell and Gossett, 1997). In contrast, the addition of fast-release H<sub>2</sub> donors ethanol, lactate, and acetate did not result in complete dechlorination. However, both ethanol and lactate did support sustained dechlorination during long-term tests. In some cases, the addition of acetate and methanol to laboratory microcosms with PCE contaminated soil did not enhance dechlorination (Gibson and Sewell, 1992). Complex substrates such as molasses and yeast extract have been shown to result in higher dechlorination levels than simple substrates (Lee et al., 1997; Odem et al., 1995; Rasmussen et al., 1994). Apparently, the fate of amended electron donors and the dynamic changes of microbial populations responsible for reductive dechlorination within soils are still not well understood.

#### *Aerobic Degradation of Chlorinated Solvents*

Under aerobic conditions, microbial degradation of chlorinated solvents to non-toxic products can occur by metabolic or cometabolic transformation reactions. DCE and VC have both been shown to be aerobically degraded in energy-yielding reactions. Recently, several aerobic strains that are capable of using VC as primary carbon and energy source have been isolated. These aerobic microorganisms include *Mycobacterium* sp. (Hartmans and De Bont, 1992), *Rhodococcus* sp. (Malachowsky et al., 1994), *Actinomycetales* sp. (Phelps et al., 1991), and *Nitrosomonas* sp. (Vanelli et al., 1990). It is suggested that these VC-utilizers may not play significant roles in contaminated site remediation due to their long doubling time.

While there have been no reports of aerobic cultures that can oxidize TCE for growth, methanotrophs are one group of bacteria that can cometabolically oxidize chlorinated solvents such as TCE, DCE, and VC to carbon dioxide and chloride ions. These organisms utilize methane as their primary carbon and energy source and produce methane monooxygenase, a key enzyme that is involved in the oxidation of methane. The same enzyme can also cometabolically oxidize chlorinated solvents. Typically, the chloroethenes are initially oxidized to chloroethene epoxides, which in turn decompose into various readily degradable chlorinated and non-chlorinated acids, alcohols or aldehydes, and carbon monoxide (Oldenhuis et al., 1989; Strandberg et al., 1989; Tsien et al., 1989; Little et al., 1988; Alvarez-Cohen and McCarty, 1991; Neuman and Wackett, 1991; Fox et al., 1990; Chang and Alvarez-Cohen, 1996). Anaerobic reductive dechlorination has also been shown to occur under bulk aerobic conditions

dominated by aerobic co-metabolic biodegradation both in the field and in soil columns (Enzien et al., 1994)

### **3.0 Scope**

Launch Complex 34 at Cape Canaveral Air Station in Florida is the test site for the remediation technology evaluation study. Separate testing plots will be established for each of the following three remediation technologies:

1. Six-Phase Heating™ (SPH)
2. In-Situ Oxidation (OX)
3. Steam Injection (SI)

Soil core samples and groundwater samples at different depths (subsurface layers) from each plot will be collected and analyzed by microbiology and molecular biology methods before and after remediation treatment in order to determine the effect of the treatments on the indigenous microbial population.

### **4.0 Analytical Approach and Justification**

Several different microbiology and molecular analysis will be conducted to evaluate the effect of the remediation technologies used on the microbial community. The following analyses will be conducted:

- Total Heterotrophic Counts
- Viability Analysis
- Coliform and *Legionella* Analysis
- PLFA Analysis
- DNA Analysis

At this time, there are no fool-proof, broadly applicable methods for functionally characterizing microbial communities. The combination of assays we propose will provide a broadly based characterization of the microbial community by utilizing a crude phylogenetic characterization (PLFA), DNA-based characterization of community components, and microscopic counts of viable (aerobic and anaerobic) bacteria and total bacteria. We anticipate that this array of methods that we will help avoid some of the common pitfalls of environmental microbiology studies generally (Madsen, 1998).

*Heterotrophic Counts Analysis.* The concentration of culturable bacteria in a subset of samples collected from each plot at each event will be done using very low carbon availability media such as 0.1% PTYG or dilute soil-extract media amended with citrate and formate. This has been found to give the best overall recovery of subsurface bacteria (Balkwill, 1989). These viable counts can be done using either MPN or plating techniques for both soil and water. These analyses can be done both under aerobic or anaerobic conditions (Gas-Pak) to provide an estimate of changes in culturable bacteria. This analysis should be used more as a check to verify changes in viable biomass changes, community shifts from anaerobic to aerobic, and direct effects that these remediation technologies may have on the culturability of indigenous

bacteria. These data will help determine if these more conventional microbiological analyses can be used to monitor the effects of the remediation technologies in future applications.

*Viability Analysis.* In addition, the proportion of live and dead bacteria in these samples will be determined using a fluorescence-based assay (Molecular Probes, LIVE/DEAD® BacLight™ Viability Kit). Since these technologies, especially the thermal ones, may kill bacteria it is important to determine the proportion of the total bacteria observed are dead and how this proportion is changed by the remediation technology being tested. Note: dead bacteria will still be visible by direct count, and thus you could have a total count of 10 billion cells/ml and yet no biological activity because they are all dead.

*Coliform and Legionella Analysis.* Water samples, collected near the sewage outfall and a few, will be analyzed for total coliforms. One-two liter samples will be collected specifically for this analysis. Samples will be shipped to BMI on ice for inventory and sample management. Coliforms are the primary indicator of human fecal contamination and thus the potential for presence of human pathogens. Since the site has a long-term sewage outfall at the edge of the test beds and since this environment is generally warm and contains high levels of nutrients it is possible that human pathogens may have survived and may be stimulated by the remediation technologies being tested. The coliform analyses of groundwater samples will verify if pathogens could be present. If initial screening indicates no coliforms than this sampling can be dropped; however, if coliforms are present it may be necessary to expand this analysis to determine the extent of their influence and the effect of that the remediation technology is having on them. *Legionella pneumophila* is a frank human pathogen that causes legionnaires disease (an often fatal pneumonia) that is found widely in the environment. It can become a problem in areas that are thermally altered, eg. nuclear reactor cooling reservoirs, pools, cooling towers, air conditioners, etc. A preliminary study done at SRS during a demonstration of radio frequency heating suggested that thermal alteration of the vadose zone could increase the density of legionella in the sediment. Since there is a sewage outfall nearby, since two of the remediation technologies are thermal, and since the remediation technologies are extracting VOC from the subsurface it would be prudent to test the subsurface for changes in *Legionella pneumophila*. This can be done by using commercially available DNA probes for *Legionella pneumophila* and testing both the soil and groundwater samples being analyzed for nucleic acid probes. This adds very little expense and can be done as part of that analyses, see below.

*PLFA/FAME Analysis.* Phospholipid ester-linked fatty acids (PLFA) and Fatty Acid Methyl Ester (FAME) analysis can measure viable biomass, characterize the types of organisms, and determine the physiological status of the microbial community. Aliquots of each sample (100 g soil and 1-2 L water) will be shipped to frozen to EPA for analysis. The PLFA method is based on extraction and GC/MS analysis of "signature" lipid biomarkers from the cell membranes and walls of microorganisms. A profile of the fatty acids and other lipids is used to determine the characteristics of the microbial community. Water will be filtered with organic free filters in the field and shipped to EPA frozen. The filter can be used to extract both nucleic acids for probe analyses and lipids for PLFA/FAME analyses. Depending on the biomass in the water 1-10 liters will need to be filtered for each sample.

*DNA Analysis.* DNA probe analysis allow examination of sediment and water samples directly for community structure, and functional components by determining the frequency and abundance to certain enzyme systems critical to biogeochemistry and biodegradation potential of that environment. Sediment samples will be collected aseptically in sleeves and shipped frozen to EPA. These sediment samples will then be extracted and the DNA analyzed for presence of certain probes for specific genetically elements. Water samples will be filtered in the field to remove the microbiota and shipped frozen to EPA for subsequent extraction and probing. The Universal probe 1390 and Bacterial domain probe 338 will help quantify the DNA extracted from the samples. This information will be useful to determine the portion of DNA that is of bacterial origin and the amount of DNA to be used in the analysis of specific bacterial groups. Transformation of chlorinated ethenes by aerobic methylotrophic bacteria that use the methane

monooxygenase enzyme has been reported (Little et al., 1988). Methanotrophs can be separated into coherent phylogenetic clusters that share common physiological characteristics (Murrell, 1998) making the use of 16S rRNA probe technology useful for studying their ecology. Therefore, this study will use 16S rRNA-targeted probes, Ser-987 and RuMP-998, to detect Type II and Type I methanotrophs, respectively. Together, these probes will be used to monitor shifts in methanotroph population numbers that may result from the application of the oxidation technology. Reductive dechlorination of chlorinated ethenes has also been reported under anaerobic conditions. Therefore, we propose the use of archaea domain (Arch-915) and sulfate-reducing specific probes (Dsv-689) to assess microbial communities involved in reductive dechlorination. The characterization of enzymes capable of reductive dehalogenation such as the dehalogenase of *Dehalospirillum multivorans* (Neumann et al., 1995) or the PCE reductive-dehalogenase of *Dehalococcoides ethenogenes* (Maymo-Gatell et al., 1999) provides promise for future gene probe design. As these gene probes become available, they will be utilized for this study. The detection of *Legionella* has been improved using a combined approach of PCR primers and oligonucleotide probe that target the 16S rRNA gene has been reported (Miyamoto et al., 1997; Maiwald et al., 1998). These PCR primers and probes will be used in this study to assess the effects of steam injection on members of this species. The following table provides the list of 16S rRNA-targeted probes that we propose to use in this study.

Target	Probe/Primer Name	Target site <sup>a</sup>	Probe/Primer Sequence 5'--3'	Reference
Universal	S-* Univ-1390-a-A-18	1407-1390	GACGGGCGGTGTGTACAA	Zheng et al., 1996
	S-D-Bact-0338-a-A-18	338-355	GCTGCCTCCCGTAGGAGT	Amann et al., 1990a
Bacteria domain	S-D-Arch-0915-a-A-20	915-934	GTGCTCCCCGCCAATTCT	Amann et al., 1990b
	S-F-Dsv-0687-a-A-16	687-702	TACGGATTTCACTCCT	Devereux et al., 1992
<i>Desulfovibrio</i> spp.	S-* M.Ser-0987-a-A-22	987-1008	CCATACCGGACATGTCAAAAGC	Brusseau et al., 1994
	S-* M.RuMP-0998-a-A-20	988-1007	GATTCTCTGGATGTCAAGGG	Brusseau et al., 1994
<i>Type II Methanotrophs</i>	<i>Legionella</i> CP2 Probe	649-630	CAACCAGTATTATCTGACCG	Jonas et al., 1995
	Primer LEG 225	225-244	AAGATTAGCCTGCGTCCGAT	Miyamoto et al., 1997
<i>Type I Methanotrophs</i>	Primer LEG 858	880-859	GTCAAATTATCGCGTTTGCT	Miyamoto et al., 1997

<sup>a</sup> *Escherichia coli* numbering

In addition to hybridization of 16S rRNA gene probes hybridization to DNA extracted by a direct method, we will also utilize the denaturing gradient gel electrophoresis (DGGE) described in Muyzer et al., 1996. The DGGE method has been used to detect overall shifts in reductively dechlorinating microbial communities (Flynn et al., 2000). If significant shifts are observed, the DNA bands will be sequenced to analyzed the genetic diversity of the communities.

## **5.0 Sample Collection, Transport, and Storage**

In each test plot, soil samples of approximately 500-g each (250 g frozen for DNA/PLFA analysis; 250 g ambient for microbial counts) will be collected using sterile brass core cylinders. Each cylinder holds approximately 250 g of soil. Sterilization of soil sample containers will involve detergent wash, water wash, heating (100 C), and alcohol wash. Polyethylene caps will not be heated, just sterilized with alcohol. Sterilization of drilling equipment will involve steam cleaning between samples.

Five borings per test plot will be used to collect aquifer samples at four depths (capillary fringe, upper sand unit [USU], middle fine grained unit [MFGU], and lower sand unit [LSU]). In addition, groundwater samples will be collected from two well clusters at three depths per plot (USU, MFGU, and LSU). Control samples from an unaffected control area will be collected under the same sampling regime. Soil controls will be collected from five locations, four depths each for consistency with treatment plot samples. Similarly, groundwater controls will be collected from 2 well clusters, at 3 depths each, if available.

Samples will be collected at four events for each technology/plot within two phases:

### **Phase 1 (June '99 – Sep '00)**

- T<0 month (pretreatment for SPH and OX)
- T= 0 months (post treatment; SPH and OX)
- T<0 month (pretreatment; SI)

### **Phase 2 (Sep '00 – Sep '01)**

- T= 6 months (post-treatment; SPH, OX, and SI)
- T= 12 months (post-treatment; SPH )

Tables 1 and 2 show the number of soil and groundwater samples involved. Table 3 shows the sampling requirements for this evaluation. Immediately after soil samples are retrieved from the borings, the collection cylinders will be tightly capped and sealed to minimize changes in environmental conditions, primarily oxygen content, of the samples. This will subsequently minimize adverse effects to the microbial population during sample transport. Samples for DNA/PLFA analysis will be frozen under nitrogen and shipped via express mail. Samples for microbial counts will be shipped at ambient temperature to an off-site lab designated by the IDC. Microbiology analysis will be conducted within 24 hours of sample collection. Approximately 5-10 g aliquots from each sample will be stored at <-60°C for molecular analysis. The study will be conducted over the course of 1.5 years in which two of the three remediation treatment methods will be demonstrated simultaneously.

Soil and groundwater sample from the region near the historical sewage outfall will be collected and analyzed as shown in Table 3.

As shown in Table 3, groundwater samples will include unfiltered groundwater (for microbial counts) and filters (for DNA/PLFA analysis) from filtration of 1 to 4 L of groundwater. Anodisc™ filters will be used and filtration apparatus will be autoclaved for 20 minutes between samples.

**Table 1. Overall Soil Sample Collection Requirement**

Plot (Remediation Treatment)	"Event" or Time Points (<0, 0, 6, 12 mo.)	Depths (5, 15, 30, 45 ft.)	Sampling Locations per Plot	Total # Soil Samples Collected Per Plot	Total # of Soil Samples Collected
SPH <sup>a</sup>	3	4	5	80	344
OX <sup>b</sup>	3	4	5	80	
SI	4	4	5	80	
Control	4	4	5	80	
Baseline (T<0 for SPH and OX)	1	4	3 <sup>c</sup>	12	
Sewage Outfall	1	4	3	12	

a Fresh samples to be collected as baseline or T&lt;0; shown in last row

b Fresh samples to be collected as baseline or T&lt;0; shown in last row

c From undisturbed DNAPL area inside ESB

**Table 2. Overall Groundwater Sample Collection Requirement**

Plot (Remediation Treatment)	"Event" or Time Points (<0, 0, 6, 12 mo.)	Depths (5, 30, 45 ft.)	Sampling Well Clusters per Plot	Total # of groundwater Samples Collected Per Plot	Total # of Groundwater Samples Collected
SPH <sup>a</sup>	3	3	2	18	87
OX <sup>b</sup>	3	3	2	18	
SI	4	3	2	24	
None (control)	3	3	2	18	
Sewage Outfall	3	3	1	9	

**Table 3. Summary of Soil and Groundwater Sampling Requirements**

Medium	Plot	Native Microbes Analysis				Pathogens Analysis		
		PLFA/DNA <sup>1</sup>	Microbial <sup>2</sup>	Locations	Sample	Califor/ Legionella	Locations	Sample
<b>Soil<sup>3</sup></b>	SPH	Freeze, store	<b>Ambient, 24 hrs</b>	5 cores per plot, 4 depths	2x250 g	NA	NA	NA
	Oxidation	Freeze, store	<b>Ambient, 24 hrs</b>		2x250 g	NA	NA	NA
	Steam Injection	Freeze, store	<b>Ambient, 24 hrs</b>		2x250 g	NA	NA	NA
	Control	Freeze, store	<b>Ambient, 24 hrs</b>		2x250 g	NA	NA	NA
	<b>Baseline</b>	Freeze, store	<b>Ambient, 24 hrs</b>	Inside ESB; 3 cores 4 depths	2x250 g	NA	NA	NA
	<b>Sewage Outfall</b>		NA	3 cores near sewage outfall at 4 depths each				2x250 g
	<b>Ground water<sup>4</sup></b>	<i>Filters from 1-4 L filtering, Freeze</i>	<i>500 mL unfiltered in Whirl-Pak, ambient</i>	<b>PA-13S/D and PA-14S/D</b>		NA	NA	NA
<b>Oxidation</b>	<i>Filters from 1-4 L filtering, Freeze</i>		<i>500 mL unfiltered in Whirl-Pak, ambient</i>	<b>BAT-2S/I/D and BAT-5S/I/D</b>		NA	NA	NA
	<b>Steam Injection</b>		<i>Filters from 1-4 L filtering, Freeze</i>	<i>500 mL unfiltered in Whirl-Pak, ambient</i>		<b>PA-16S/I/D and PA-17S/I/D</b>	NA	NA
	<b>Control</b>		<i>Filters from 1-4 L filtering, Freeze</i>	<i>500 mL unfiltered in Whirl-Pak, ambient</i>		<b>IW-1I/D and PA-1S/I/D</b>	NA	NA
	<b>Sewage Outfall</b>		NA	NA		<i>1 L unfiltered in Whirl-Pak</i>	<b>IW-17I/D and PA-15</b>	

*Shaded and italicized text indicates new sampling and analysis scope that needs to be funded. Bold and italics indicates that the sampling is funded but the analysis is not funded.*

NA: Not applicable

<sup>1</sup> DNA/PLFA: DNA/PLFA Analysis. Sleeves are frozen in Nitrogen before shipping.

<sup>2</sup> Microbial: Total Heterotrophic Counts/Viability Analysis. Sleeves are shipped at ambient temperature for analysis within 24 hrs.

<sup>3</sup> Soil samples will be collected in 6"-long 1.5"-dia brass sleeves, then capped. Brass sleeves need to be autoclaved and wiped with ethanol just before use. Caps need to be wiped with ethanol prior to use.

<sup>4</sup> 3 to 4 liters of groundwater will be filtered and filters will be shipped for analysis. Filters for DNA analysis will be frozen under N2 before shipping. Groundwater for microbial analysis will be shipped at ambient temperature for analysis within 24 hrs. Between samples, filtration apparatus needs to be autoclaved for 20 minutes.

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## **E.2 Microbiological Evaluation Sampling Procedures**

### ***Work Plan for Biological Soil and Groundwater Sampling and Procedure***

*Battelle*  
January 4, 2001

#### **Soil Sampling**

Soil samples are collected at four discrete depths in the subsurface with a 2-inch diameter sample barrel containing sample sleeves. Once the sample is retrieved, the sleeves are removed from the sample barrel, capped at both ends, and preserved accordingly. The sleeves are then transported to off-site analytical laboratories for analyses. Field personnel should change their gloves after each sample to prevent cross-contamination. The details of the sampling are provided below:

**Samplers:** The Mostap™ is 20-inch long with a 1.5-inch diameter and the Macro-core™ sampler is about 33-inch long with a 2-inch diameter. Sleeves (brass or stainless steel) are placed in a sample sampler (Macro-core™ or Mostap™). Brass sleeves with 1.5-inch diameter and 6-inch long are used for a Cone-Penetrometer (CPT) rig from U.S. EPA. Stainless steel sleeves with 2-inch diameter and 6-inch long are used with a rig from a contracted drilling company rig.

For Mostap™, three of these brass sleeves and one spacer will be placed in the sampler. For the Macro- Core™ sampler, five 6-inch long stainless sleeves and one spacer are required. All sleeves and spacers need to be sterilized and the procedure is as follows.

**Procedures:** sampling preparation procedures are as follows:

1. Preparation for sterilization:
  - Dip sleeves in an isopropyl alcohol bath to clean surface inside and outside
  - Air-dry the sleeves at ambient temperature until they are dried
  - Wrap up the sleeves with aluminum foil
  - Place the aluminum foil-wrapped sleeves in an autoclavable bag and keep the bag in a heat-resistant plastic container
  - Place the container in an autoclave for 30 minutes at about 140 °C
  - Once the autoclaving is completed, let the sleeves sit until the materials are cool, and then pack and ship to the field site.
2. In the field, drive the sample barrel down to four different depths: approximately 8 (capillary fringe), 15 (USU below water table), 23 (MFGU), and 45 (LSU) ft below ground surface (bgs). Once the sample barrel is withdrawn, the sleeves are extruded from the sample barrel. Each sleeve immediately capped with plastic end caps that have been previously wiped with isopropyl alcohol. After capping, clear labeling of the sleeve is required including sample site, sample ID, actual depth of the sample, collection date and time, percentage of recovery in each sleeve, and markings for top and bottom of the sample sleeves.

Sample Preservation: one of the sleeves is kept at ambient temperature. At least, two of the sleeves need to be frozen in liquid nitrogen immediately then stored in a freezer at temperature below freezing point.

Off-site Laboratories: The sample sleeve at ambient temperature is to be shipped off to Florida State University for analyses of *live/dead stain test* and *aerobic and anaerobic heterotrophic counting*. The frozen samples are shipped off to EPA Ada Laboratory, an off-site laboratory for *DNA* and *Phospholipids Fatty Acid Analyses (PLFA)*.

3. Decontamination Procedure: after the samples are extruded, the sample barrel used to collect the soil samples needs to be disassembled and cleaned in Alconox® detergent mixed water. The sample barrel is then rinsed with tap water, followed by de-ionized (DI) water. The sample barrel is air-dried and rinsed with isopropyl alcohol before the next sampling.

## Groundwater Sampling

Groundwater sampling involves collection of groundwater from performance monitoring wells using a peristaltic pump and Teflon® tubing. During the groundwater sampling, unfiltered water samples will be collected. Large volume of groundwater will be filtered through in-line filtration unit and the filter will be retrieved and this filter will be preserved necessarily.

1. Preparation for Sterilization
  - Dip in-line filter holders in an alcohol bath and air-dry
  - Wrap each filter unit up in aluminum foil
  - Place them in an autoclavable bag and keep the bag in a heat resistant container
  - Autoclave the container with filters for 30 minutes at 140°C
  - Once the autoclaving is completed, let the sleeves sit until the materials are cool, and then pack and ship to the field site.
2. Materials and Equipments: Non-carbon Anodisc® 0.2  $\mu\text{m}$  pore size supported filters, filtration equipment, a low-flow pump, Teflon tubing and Viton® tubing and a vacuum (or pressure) pump.

The dimensions of the Anodisc® filters are 0.2 micron pore size and 47-mm diameter. The filters are pre-sterilized by the manufacturer. Each filter is carefully placed inside a filter holder case. A forceps is used to place a filter in either an in-line polycarbon filter holder or in an off-line filter holder. The filter is very brittle and should be handled delicately.

3. Filter samples by using an in-line filter holder: An Anodisc® filter is wetted with D.I. water and placed on the influent end of the filter holder. A rubber o-ring is gently placed on the filter holder. The filter holder is connected to the effluent end of the peristaltic pump with Teflon® tubing and approximately one liter of groundwater is filtered through it. The filter is retrieved from the filter holder carefully with forceps and placed in a Whirl-Pak®. The filter, along with the bag, is deep frozen under liquid nitrogen and stored in a freezer until shipping.
4. Filter Samples by using an filtration unit: To use this filtration device, a vacuum or pressure pump is required to pull or push the water through. Influent water from a low-flow peristaltic pump goes into a funnel-shaped water container. The filter will be retrieved after water

filtration and the filtrated water can be disposed. The filter is frozen immediately in liquid nitrogen and stored then kept in a freezer.

5. Unfiltered Groundwater Samples: unfiltered groundwater samples are collected into each 500-mL Whirl-Pak® bag. This water sample is kept at ambient temperature.
6. Labeling includes sample ID, same date and time, and site ID on the Whirl-Pak® after the sample is placed with a permanent marker.
7. Sterilization of the filter holders may be done as follows:
  - Clean forceps and filter holder in warm detergent mixed water, then rinse with isopropyl alcohol and air-dry at room temperature.
  - The cleaned forceps and filter holders are wrapped in aluminum foil and taped with a piece of autoclave tape that indicates when the autoclaving is completed.
  - These items are then placed in an autoclavable bag and the bag is placed in an autoclave for about 30 minutes at 140 °C. After taking them out of the autoclave, the items sit until cool.
8. Off-site laboratories: The unfiltered water samples are shipped off to Florida State University for **aerobic and anaerobic heterotrophic count tests and viability analysis** at ambient temperature within 24 hours. The filter samples are shipped off in dry-ice condition to EPA Ada Lab for **DNA, PLFA, and Legionella analyses**.

## Sample Locations

### Soil Sampling

Five biological sampling locations will be located in each of three plots in January 2001. One duplicate samples will be collected from one of the five boring locations in each plot (Figure 1). At each location, soil samples will be collected at four depths (Capillary fringe, USU, MFGU and LSU). Soil sampling procedures are described in previous sections. Summary of the biological soil sampling is shown in Table 1.

**Table 1. Biological Soil Sampling in January-February 2001**

Plot	Event	Number of Coring	Total Number of Samples
Steam Injection	Pre-Demo (T<0)	5	20 + 1 (Dup)
Oxidation	6 Months After (T=6)	5	20 + 1 (Dup)
Control	-	5	20
SPH*	Post-Demo (T=0)	5	20 + 1 (Dup)

\* In February along with chemical coring in Oxidation plot.

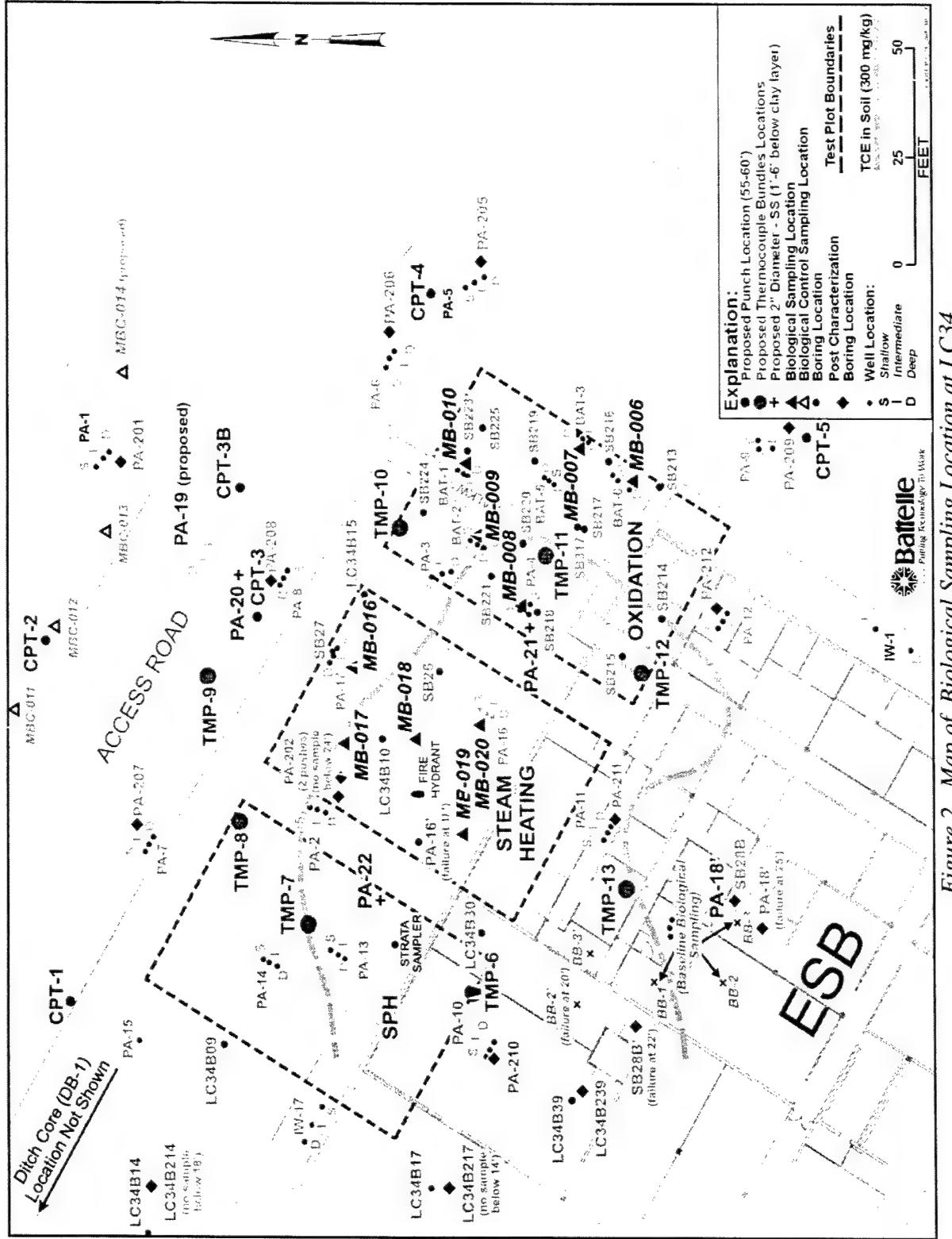
### Groundwater Sampling

Biological groundwater samples will be collected from wells within the Steam Injection plot, the Oxidation plot, and the Six-Phase Heating plot in January 2001 in

conjunction with the biological soil sampling. Groundwater sampling will be completed as described previously. One QA groundwater sample will be completed at a random well location. Table 2 summarizes the performance monitoring wells (Figure 1) to be sampled.

**Table 2. Biological Groundwater Sampling in January-February 2001**

<b>Plot</b>	<b>Event</b>	<b>Well ID</b>	<b>Total Number of Samples</b>
Steam Injection	Pre-Demo (T<0)	PA-16S/I/D PA-17S/I/D	6
Oxidation	6 Months After (T=6)	BAT-2S/I/D BAT-5S/I/D	6
SPH	Post-Demo (T=0)	PA-13S/D PA-14S/D	4
Control	-	PA-18S/I/D	3
QA	-	random	1



*Figure 2. Map of Biological Sampling Location at LC34*

### **E.3 Microbiological Evaluation Results**

Some results of the microbiological evaluation described in Appendix E.1 are contained in Tables E-1 and E-2. Only the soil and groundwater samples collected for microbial counts analysis have been analyzed. The samples collected for DNA probes analysis were frozen under nitrogen and shipped to the U.S. EPA's R.S. Kerr Environmental Research Center and are awaiting analysis.

Table E-1 describes the microbial counts analysis of soil samples that represent predemonstration (baseline or T<0) and postdemonstration (Treated, T=0) conditions in the Oxidation Plot. The results of an extended monitoring event (Treated, T=6) conducted 6 months after the end of oxidation treatment in the plot are also listed. The control samples (control, untreated) are samples collected from an unaffected (TCE contaminated, but not in the oxidation zone) portion of the Launch Complex 34 aquifer; these control samples were collected at the same time as the postdemonstration (T=0) sampling event. Table E-2 lists similar results for groundwater samples.

Because of the large variability in the data, only a few general trends were identified. As seen in Table E-1, both aerobic and anaerobic plate counts in the soil were lower in the treated soil (T=0) compared to the untreated (baseline) soil or control samples. In some regions, microbial populations appear to have been eliminated completely. This indicates that oxidation diminishes the microbial populations in the short term. The differences in surviving population numbers in different parts of the plot are probably indicative of the differential distribution of the oxidant. However, six months later, the microbial populations reappeared strongly in both aerobic and anaerobic conditions.

As seen in Table E-2, the groundwater analysis shows similar trends. Aerobic and anaerobic counts in the groundwater were diminished by the oxidation treatment, but rebounded within six months.

This indicates that the chemical oxidation application reduces microbial populations in the short-term, but the populations rebound within a six-month period. Rebound in microbial populations is important because of the reliance on natural attenuation to address any residual contamination in the aquifer, following chemical oxidation treatment.

**Table E-1. Results of Microbial Counts of Soil Samples**

Sample ID	Top Depth	Bottom Depth	Aerobic Plate Counts	Anaerobic Viable Counts
	ft bgs	ft bgs	CFU/g or mL*	Cells/g or mL
<b><i>Soil Core Samples</i></b>				
<b><i>Baseline Samples (June 2000)</i></b>				
BB1-A	7	9	15,849	7,943
BB1-A	15.5	17	<316.23	158
BB2-A	7	9	19,953	31,623
BB3-A	9	11	12,589	3,162
BB3-A	15	17	<316.23	<1.78
BB-1-7.0	6.5	7.0	79,432.8	1,584,893.2
BB-1-14.0	13.5	14.0	<316.2	631.0
BB-1-24.0	23.5	24.0	199.5	1,584.9
BB-1-44.0	43.5	44.0	<316.2	316.2
BB-2-7.0	6.5	7.0	19,952.6	19,952.6
BB-2-7.0	6.5	7.0	31,622.8	10,000.0
BB-2-16.5	16.0	16.5	2,511.9	3,162.3
BB-2-23.0	22.5	23.0	1,584,893.2	1,258,925.4
BB-2-24.0	23.5	24.0	<316.2	No Growth
BB-2-44.0	43.5	44.0	<316.2	251.2
BB-3-7.0	6.5	7.0	199,526.2	158,489.3
BB-3-14.0	13.5	14.0	6,309.6	50,118.7
BB-3-24.0	23.5	24.0	631.0	501.2
BB-3-44.0	43.5	44.0	25,118.9	63,095.7
<b><i>Control Samples, Untreated (June 2000 except MBC014 in January 2001)</i></b>				
MBC011-A-1	6	7.5	1,584,893	1,584,893
MBC011-A-2	15	16.5	501,187	794,328
MBC011-A-3	30	31.5	15,849	7,943
MBC011-A-4	40	41.5	316,228	63,096
MBC012-A-1	6	7.5	25,119	50,119
MBC012-A-3	30	31.5	125,893	6,310
MBC012-A-4	40	41.5	1,585	794
MBC013-A-1	6	7.5	125,893	19,953
MBC013-A-2	15	16.5	1,259	2,512
MBC013-A-3	30	31.5	501	794
MBC013-A-4	40	41.5	7,943	5,012
MBC014	7	7.5	63,095.73	79,432.82
MBC014	16	16.5	100,000.00	316,227.77
MBC014	31	31.5	39,810.72	79,432.82
MBC014	41	41.5	7,943.28	25,118.86
MBC015-A-1	6	7.5	3,981	5,012
MBC015-A-3	35	36.5	316	251
<b><i>Oxidation Plot, Treated T=0 (June 2000)</i></b>				
MB06-A-1	6	7.5	6,309,573	1,584,893
MB06-A-2	15	16.5	7,943	6,310
MB06-A-3	30	31.5	7,943	31,623

**Table E-1. Results of Microbial Counts of Soil Samples**

Sample ID	Top Depth	Bottom Depth	Aerobic Plate Counts	Anaerobic Viable Counts
	ft bgs	ft bgs	CFU/g or mL*	Cells/g or mL
MB06-A-4	40	41.5	199,526	501,187
MB07-A-1	6	7.5	7,943,282	>1,584,893.19
MB07-A-3	17	18.5	<316.23	<1.78
MB07-A-4	30	31.5	1,584,893	1,584,893
MB07-A-5	40	41.5	7,943,282	>1,584,893.19
MB08-A-1	6	7.5	100,000,000	1,584,893
MB08-A-2	26	16.5	<316.23	<1.78
MB08-A-3	30	31.5	<316.23	<1.78
MB08-A-4	40	41.5	7,943	1,259
MB09-A-2	15	16.5	<316.23	<1.78
MB09-A-3	30	31.5	398,107	1,584,893
MB09-A-4	40	41.5	199,526	501,187
MB10-A-1	6	7.5	3,162,278	1,584,893
MB10-A-3	30	31.5	1,259	5,012
MB10-A-4	40	41.5	199,526	1,584,893
<b>Oxidation Plot, Treated T=6 (January 2001)</b>				
MB-106A	10	10.5	3,162,277.66	12,589,254.12
MB-106B	16	16.5	1,995,262.31	5,011,872.34
MB-106C	31	31.5	1,258,925.41	3,162,277.66
MB-106D	41	41.5	316,227.77	1,000,000.00
MB-107A	7	7.5	6,309,573.44	7,943,282.35
MB-107B	17.5	18	7,943,282.35	19,952,623.15
MB-107C	31	31.5	630,957.34	316,227.77
MB-107D	41	41.5	794,328.23	3,981,071.71
MB-108A	6	6.5	63,095.73	316,227.77
MB-108B	15	15.5	501,187.23	1,584,893.19
MB-108C	30	30.5	398,107.17	1,584,893.19
MB-108D	40	40.5	19,952.62	50,118.72
MB-109A	8	8.5	63,095,734.45	>31,622,776.60
MB-109B	16	16.5	398,107.17	501,187.23
MB-109C	31	31.5	125,892.54	251,188.64
MB-109D	33	33.5	630,957.34	1,584,893.19
MB-109E	41	41.5	25,118.86	501,187.23
MB-110A	7	7.5	19,952.62	251,188.64
MB-110B	16	16.5	7,943.28	199,526.23
MB-110C	32	32.5	15,848.93	7,943.28
MB-110D	41	41.5	158,489.32	125,892.54

NA: Not available.

bgs: Below ground surface.

\*CFU: Colony-forming units (roughly, number of culturable cells).

**Table E-2. Results of Microbial Counts Groundwater Samples**

Sample ID	Top Depth	Bottom Depth	Aerobic Plate Counts	Anaerobic Viable Counts
	ft bgs	ft bgs	CFU/g or mL*	Cells/g or mL
<b>Groundwater Samples</b>				
<i>Control Samples, Untreated, Distant Wells</i>				
IW-1I	NA	NA	79,433	>1,584,893.19
IW-1D	NA	NA	5,012	15,849
PA-1S	NA	NA	15,849	158,489
PA-1I	NA	NA	501,187	>1,584,893.19
PA-1D	NA	NA	39,811	1,584,893
<i>Oxidation Plot Wells, Treated, T=0 (June 2000)</i>				
BAT-2S	NA	NA	<31.62	25
BAT-2I	NA	NA	39,811	100,000
BAT-2D	NA	NA	630,957	1,584,893
BAT-5S	NA	NA	12,589	1,584,893
BAT-5I	NA	NA	32	25
BAT-5D	NA	NA	39,811	31,623
<i>Oxidation Plot Wells, Treated, T=6 (January 2001)</i>				
BAT-2S	NA	NA	<31.7	<1.78
BAT-2I	NA	NA	125,893	1,584,893.19
BAT-2D	NA	NA	6,310	50,118.72
BAT-5S	NA	NA	125,893	1,995,262.31
BAT-5I	NA	NA	158,489	3,981,071.71
BAT-5D	NA	NA	2,512	12,589.25
<i>SPH Plot Wells, Treated, T=0 (January 2001)</i>				
PA-13S	NA	NA	<31.62	31.62
PA-13D	NA	NA	<31.62	<1.78
PA-14S	NA	NA	<31.62	158.49
PA-14D	NA	NA	<31.62	<1.78
<i>SPH Plot Perimeter Wells, T=0 (January 2001)</i>				
PA-15	NA	NA	<31.62	25
PA-15-DUP	NA	NA	<31.62	<1.78
IW-17I	NA	NA	<31.62	316
IW-17D	NA	NA	<31.62	2

NA: Not available.

bgs: Below ground surface.

\*CFU: Colony-forming units (roughly, number of culturable cells).

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## **Appendix F. Surface Emissions Testing**

- F.1 Surface Emission Test Methodology**
- F.2 Surface Emission Test Results**

## **F.1 Surface Emissions Testing Methods and Procedures**

One of the concerns about the technology as a means of soil and groundwater remediation was the possibility of transferring chlorinated volatile organic compounds (CVOCs) to the atmosphere through the ground surface or injection and monitoring wells. Emissions testing was performed to obtain a qualitative picture of VOC losses to the atmosphere from a mass balance perspective. Trying to quantify these discharges to the atmosphere went well beyond the resources of this study. The sampling and analytical methodologies for the emissions tests are presented in the following subsections.

### **F.1.1 Dynamic Surface Emissions Sampling Methodology**

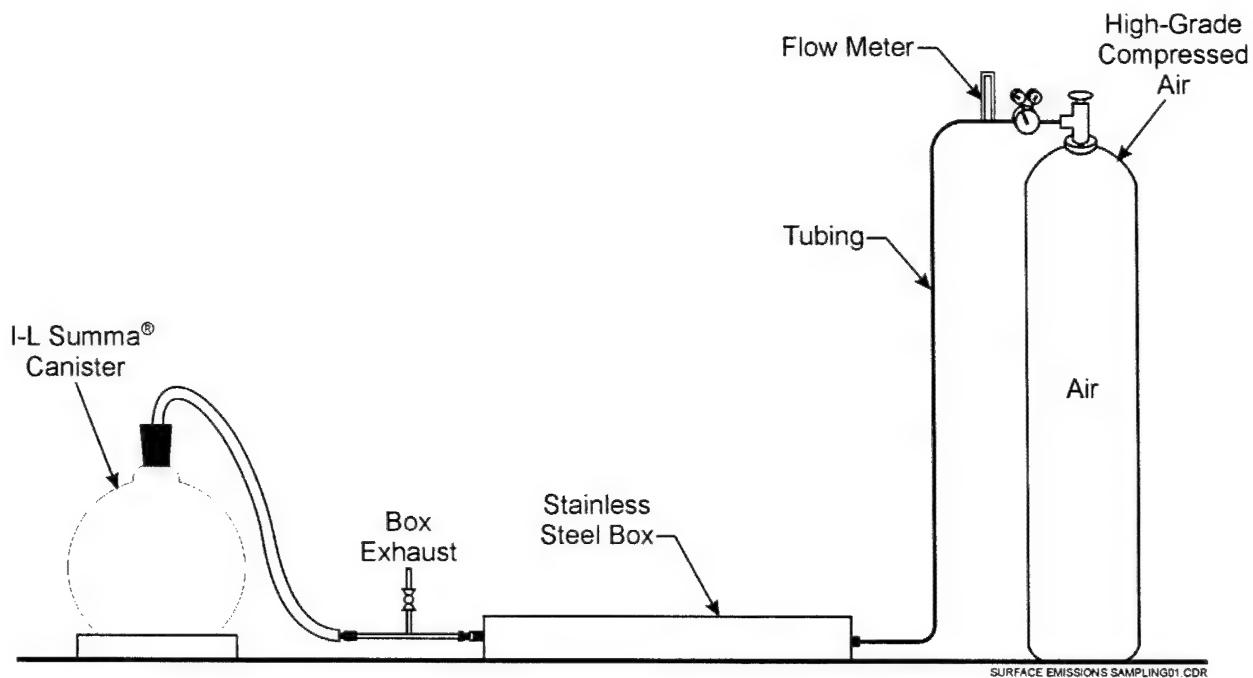
A dynamic surface emissions sampling method was used at the LC34 site. This method involves enclosing an area of soil under an inert box designed to allow the purging of the enclosure with high-purity air (Dupont, 1987). The box was purged with high-purity air for two hours to remove any ambient air from the region above the soil and to allow equilibrium to be established between the VOCs emitted from the soil and the organic-free air. The airstream was then sampled by drawing a known volume of the VOC/pure air mixture through a 1-L Summa canister. The Summa canister captured any organics associated with surface emissions from the test plot. The Summa canisters were then shipped to the off-site laboratory with a completed chain-of-custody form. The Summa canisters were then connected to an air sampler that was attached to a GC, which is where the concentrations of organics were quantified. These measured concentrations were used to calculate emission rates for the VOCs from the soil to the atmosphere.

A schematic diagram of the surface emissions sampling system is shown as Figure F-1. The system consists of a stainless steel box that covers a surface area of approximately 0.5 m<sup>2</sup>. The box was fitted with inlet and outlet ports for the entry and exit of high-purity air, which is supplied via a gas cylinder. Inside the box was a manifold that delivered the air supply uniformly across the soil surface. The same type of manifold was also fitted to the exit port of the box. The configuration was designed to deliver an even flow of air across the entire soil surface under the box so that a representative sample was generated. To collect the sample, the air exiting the box was pulled by vacuum into the Summa canister.

In all testing cases, a totally inert system was employed. Teflon™ tubing and stainless steel fittings were used to ensure that there was no contribution to or removal of organics from the air stream. The Summa canister was located on the backside of the emissions box so that it would not be in a position to reverse the flow of air inside the box.

### **F.1.2 Sampling Schedule**

Three surface emissions sampling locations were selected around the steam plot during the technology demonstration. The emissions box was placed strategically between two soil vapor extraction wells. The locations of the emissions sampling were chosen because this area had the highest probability of surface emissions during operations. The proposed testing occurred in the third, sixth, and ninth week of operations; these weeks were chosen because by then any vapor generated by the injection technology would be formed.



**Figure F-1. Schematic Diagram of the Surface Emissions Sampling System**

### F.1.3 Analytical Calculations

The complete analytical results from the surface emissions sampling at LC34 are presented in this final report. The data is represented temporally, reflecting the three sampling events at the site. Flux values in  $\mu\text{g}$  of compound emitted into the atmosphere per unit of time were calculated. The results from the analysis of the Summa canisters and ambient air samples are presented in the final report. The ambient air samples were collected as reference concentrations of the emission levels to the existing air quality. GC calibration data is presented to verify the precision and accuracy of the sampling/analytical method.

To calculate actual emission rates of organic compounds from the soil surface into the atmosphere, the following equation for dynamic enclosure techniques was used (McVeety, 1991):

$$F = CV_r/S \quad (\text{F-1})$$

where:   
**F** = flux in mass-area/time ( $\mu\text{g m}^2/\text{min}$ )  
**C** = the concentration of gas in units of mass/volume ( $\mu\text{g/m}^3$ )  
**V<sub>r</sub>** = volumetric flowrate of sweep gas ( $\text{m}^3/\text{min}$ )  
**S** = soil surface covered by the enclosure ( $\text{m}^2$ ).

**Table F-2. Surface Emission Test Results**

Sample ID	Sample	TCE	Sample ID	Sample	TCE
	Date	ppb (v/v)		Date	ppb (v/v)
<b>Oxidation Plot</b>					
OX-SE-1	09/30/1999	1.6	SPH-SE-1	10/08/1999	2.1
OX-SE-2	09/30/1999	2.4	SPH-SE-2	10/08/1999	3.6
OX-SE-3	10/01/1999	3.4	SPH-SE-3	10/08/1999	2
OX-SE-4	10/25/1999	0.68	SPH-SE-4	10/22/1999	13,000
OX-SE-5	10/25/1999	1.1	SPH-SE-5	10/22/1999	12,000
OX-SE-6	10/25/1999	1.4	SPH-SE-6	10/22/1999	13,000
OX-SE-7	01/17/2000	11	SPH-SE-7	01/18/2000	23
OX-SE-8	01/17/2000	7.6	SPH-SE-8	01/18/2000	78
OX-SE-9	01/17/2000	5.8	SPH-SE-9	01/18/2000	35
OX-SE-10	04/11/2000	2.6	SPH-SE-10	04/11/2000	0.93
OX-SE-11	04/11/2000	0.69	SPH-SE-11	04/11/2000	0.67
OX-SE-12	04/11/2000	1.7	SPH-SE-12	04/11/2000	<0.37
OX-SE-21	08/29/2000	16	SPH-SE-13	04/11/2000	1,300
OX-SE-22	08/29/2000	130	NA	NA	NA
OX-SE-23	08/30/2000	180	NA	NA	NA
<b>Background</b>					
DW-SE-1	10/01/1999	< 0.42	SPH-SE-14	05/09/2000	<0.39 <sup>a</sup>
DW-SE-2	10/08/1999	< 0.44	SPH-SE-15	05/09/2000	<0.39 <sup>a</sup>
DW-SE-3	10/25/1999	0.44	SPH-SE-C27	09/01/2000	<0.88
DW-SE-4	10/22/1999	6,000 <sup>b</sup>	DW-C1	04/11/2000	2.1 <sup>c</sup>
DW-SE-5	01/17/2000	< 0.38	DW-C2	05/09/2000	<0.39
DW-SE-6	04/11/2000	0.43	DW-C3	05/09/2000	<0.39
DW-SE-7	04/11/2000	0.86	NA	NA	NA
DW-SE-8	04/11/2000	0.79	NA	NA	NA
<b>Ambient Air at Shoulder Level</b>					

ppb (v/v): parts per billion by volume.

a. SPH-SE-14/15 samples were collected at an ambient elevation east and west edge of the SPH plot w/o using an air collection box.

b. Background sample (10/22/99) was taken immediately after SPH-SE-6 sample (the last sample for this event), which had an unexpectedly high concentration of 13,000 ppbv. This may indicate condensation of TCE in the emissions collection box at levels that could not be removed by the standard decontamination procedure of purging the box with air for two hours. In subsequent events (1/17/2000 background), special additional decontamination steps were taken to minimize carryover.

c. This sample was collected by holding a Summa canister at shoulder level collecting an ambient air sample to evaluate local background air.

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**Appendix G. Quality Assurance/ Quality Control Information**

Tables G-1 to G-20

**Table G-1. Results of the Extraction Procedure Performed on PA-4 Soil Samples**

Extraction Procedure Conditions		Combined		
Total Weight of Wet Soil (g) = 2,124.2		1,587.8 g dry soil from PA-4 boring		
Concentration (mg TCE/g soil) = 3.3		529.3 g deionized water		
Moisture Content of Soil (%) = 24.9		5 mL TCE		

Laboratory Extraction Sample ID	TCE Concentration in MeOH (mg/L)	TCE Mass in MeOH (mg)	TCE Concentration in Spiked Soil (mg/kg)	Theoretical TCE Mass Expected in MeOH (mg)	Percentage Recovery of Spiked TCE (%)
<b>1<sup>st</sup> Extraction procedure on same set of samples</b>					
SEP-1-1	1800.0	547.1	3252.5	744.11	73.53
SEP-1-2	1650.0	501.8	3164.9	701.26	71.55
SEP-1-3	1950.0	592.2	3782.3	692.62	85.51
SEP-1-4	1840.0	558.1	3340.2	739.13	75.51
SEP-1-5	1860.0	564.0	3533.9	705.91	79.89
SEP-1-6 (Control)	78.3	19.4	-	25.00	77.65
				Average % Recovery =	77.20
<b>2<sup>nd</sup> Extraction procedure on same set of samples</b>					
SEP-2-1	568.0	172.7	861.1	887.28	19.47
SEP-2-2	315.0	95.5	500.5	843.77	11.31
SEP-2-3	170.0	51.3	268.2	846.42	6.06
SEP-2-4	329.0	99.8	498.4	885.29	11.27
SEP-2-5	312.0	94.8	476.3	880.31	10.77
SEP-2-6 (Control)	82.6	20.4	-	25.00	81.79
				Average % Recovery =	11.78
<b>3<sup>rd</sup> Extraction procedure on same set of samples</b>					
SEP-3-1	55.8	17.0	84.6	885.96	1.91
SEP-3-2	59.0	17.9	94.2	841.77	2.13
SEP-3-3	56.8	17.2	90.1	846.42	2.04
SEP-3-4	63.0	19.1	95.2	888.61	2.15
SEP-3-5	52.2	15.8	80.0	875.99	1.81
SEP-3-6 (Control)	84.3	20.9	-	25.00	83.55
				Average % Recovery =	2.01

**Table G-2. Results and Precision of the Field Duplicate Samples Collected During the Pre- and Post-Demonstration Soil Sampling**  
**Oxidation Treatment Plot Field Duplicate Soil Samples**  
**QA/QC Target Level < 30.0 %**

Oxidation Treatment Plot Field Duplicate Soil Samples		Total Number of Soil Samples Collected = 665 Total Number of Field Duplicate Samples Analyzed = 26					
Pre-Demonstration				Post-Demonstration			
Sample ID	Sample Date	Result (mg/kg)	RPD (%)	Sample ID	Sample Date	Result (mg/kg)	RPD (%)
SB-22-16	06/22/1999	2.58	22.03	SB-225-40	05/18/2000	16.35	11.99
SB-22-16B		2.07		SB-225-40B		18.43	
SB-23-34	06/23/1999	146.89	16.03	SB-219-36	05/19/2000	13.10	94.45 <sup>(a)</sup>
SB-23-34B		125.10		SB-219-36B		36.55	
SB-24-42	06/25/1999	43.01	19.22	SB-223-34	05/19/2000	ND	169.11 <sup>(a)</sup>
SB-24-42B		35.47		SB-223-34B		11.95	
SB-21-42	06/28/1999	5,913.59	40.44 <sup>(b)</sup>	SB-224-38	05/19/2000	278.20	40.24 <sup>(a)</sup>
SB-21-42B		8,911.22		SB-224-38B		185.00	
SB-19-30	06/28/1999	184.95	6.61	SB-220-34	05/20/2000	ND	0.00
SB-19-30B		173.11		SB-220-34B		ND	
SB-18-22	06/29/1999	110.06	59.70 <sup>(a)</sup>	SB-218-20	05/22/2000	ND	0.00
SB-18-22B		59.46		SB-218-20B		ND	
SB-20-26	06/29/1999	179.81	2.72	SB-221-42	05/22/2000	65.26	13.66
SB-20-26B		184.76		SB-221-42B		56.91	
SB-17-34	06/30/1999	191.43	6.20	SB-217-30	05/23/2000	36.12	73.09 <sup>(a)</sup>
SB-17-34B		203.68		SB-217-30B		77.72	
SB-16-12	06/30/1999	0.30	4.94	SB-317-36	05/23/2000	29.44	65.15 <sup>(a)</sup>
SB-16-12B		0.28		SB-317-36B		57.89	
SB-13-32	07/01/1999	56.54	14.78	SB-213-30	05/24/2000	ND	0.00
SB-13-32B		65.56		SB-213-30B		ND	
SB-25-18	07/01/1999	1.56	41.27 <sup>(a)</sup>	SB-216-28	05/24/2000	9.98	81.42 <sup>(a)</sup>
SB-25-18B		2.37		SB-216-28B		23.68	
SB-14-40	07/15/1999	853.25	12.25	SB-215-34	06/01/2000	3,722.93	4.33
SB-14-40B		754.78		SB-215-34B		3,887.58	
SB-15-24	07/16/1999	240.81	6.57	SB-28-14	06/02/2000	28.35	11.88
SB-15-24B		225.50		SB-28-14B		25.17	

(a) Samples had high RPD values due to the effect of low (or below detect) concentrations of TCE drastically affected the RPD calculation.

(b) Samples had high RPD values probably due to high levels of DNAPL distributed heterogeneously through the soil core sample.

**Table G-3. Results of the Rinsate Blank Samples Collected During the Post-Demonstration Soil Sampling**

Total Number of Samples Collected = 357

Total Number of Field Samples Analyzed = 7

Post-Demonstration Rinsate Blank Samples			
Sample ID	Sample Date	Result (ug/L)	Comments
RB-24-1	05/18/2000	<5.0	Met QA/QC Target Criteria
RB-23-2	05/19/2000	<5.0	Met QA/QC Target Criteria
RB-220-3	05/20/2000	<5.0	Met QA/QC Target Criteria
RB-216-4	05/22/2000	<5.0	Met QA/QC Target Criteria
RB-317-5	05/23/2000	<5.0	Met QA/QC Target Criteria
RB-213-6	05/25/2000	<5.0	Met QA/QC Target Criteria
RB-26-7	05/25/2000	<5.0	Met QA/QC Target Criteria

(a) Pre-demonstration equipment blanks were not collected.

**Table G-4. Results of the Methanol Blank Samples Collected During the Pre- and Post-Demonstration Soil Sampling**  
**Oxidation Methanol Blank Soil Extraction QA/QC Samples**  
**QA/QC Target Level < 1.0 mg/kg**

Pre-Demonstration Methanol Blank Samples				Post-Demonstration Methanol Blank Samples			
Sample ID	Sample Date	Result (mg/kg)	Comments	Sample ID	Sample Date	Result (mg/kg)	Comments
SB-22-Blank	06/23/1999	<0.250	Met QA/QC Target Criteria	SB-225-Blank	05/18/2000	<0.250	Met QA/QC Target Criteria
SB-23-Blank	06/23/1999	1.800 <sup>(a)</sup>	See footnote.	SB-223-Blank	05/19/2000	<0.250	Met QA/QC Target Criteria
SB-24-Blank	06/25/1999	<0.250	Met QA/QC Target Criteria	SB-219-Blank	05/19/2000	<0.250	Met QA/QC Target Criteria
SB-21-Blank	06/28/1999	<0.250	Met QA/QC Target Criteria	SB-224-Blank	05/20/2000	<0.250	Met QA/QC Target Criteria
SB-19-Blank	06/28/1999	0.205	Met QA/QC Target Criteria	SB-220-Blank	05/20/2000	<0.250	Met QA/QC Target Criteria
SB-18-Blank	06/29/1999	8.027 <sup>(b)</sup>	See footnote.	SB-221-Blank	05/21/2000	<0.250	Met QA/QC Target Criteria
SB-20-Blank	06/29/1999	0.944	Met QA/QC Target Criteria	SB-218-Blank	05/22/2000	<0.250	Met QA/QC Target Criteria
SB-17-Blank	06/30/1999	0.205	Met QA/QC Target Criteria	SB-217-Blank	05/23/2000	<0.250	Met QA/QC Target Criteria
SB-16-Blank	06/30/1999	<0.250	Met QA/QC Target Criteria	SB-317-Blank	05/23/2000	<0.250	Met QA/QC Target Criteria
SB-13-Blank	07/01/1999	0.220	Met QA/QC Target Criteria	SB-216-Blank	05/24/2000	<0.250	Met QA/QC Target Criteria
SB-25-Blank	07/01/1999	<0.250	Met QA/QC Target Criteria	SB-213-Blank	05/24/2000	<0.250	Met QA/QC Target Criteria
SB-14-Blank	07/15/1999	<0.250	Met QA/QC Target Criteria	SB-214-Blank	05/31/2000	<0.250	Met QA/QC Target Criteria
SB-15-Blank	07/16/1999	1.228 <sup>(c)</sup>	See footnote.	SB-215-Blank	06/01/2000	<0.250	Met QA/QC Target Criteria

(a) Methanol Blank sample concentrations were below 10% of the TCE results for the samples in these batches. This batch included the following set of samples: SB-23-055 through SB-23-075

(b) Methanol Blank sample concentrations were below 10% of the TCE results for the samples in these batches. This batch included the following set of samples: SB-18-293 through SB-18-317

(c) Methanol Blank sample concentrations were below 10% of the TCE results for the samples in these batches. This batch included the following set of samples: SB-15-569 through SB-15-592

**Table G-5. Results and Precision of the Field Duplicate Samples Collected During the Pre- and Post-Demonstration Groundwater Sampling**  
**Oxidation Treatment Plot Field Duplicate Groundwater Samples**  
**QA/QC Target Level < 30.0 %**

Pre-Demonstration						Post-Demonstration					
Sample ID	Sample Date	Result (ug/L)	RPD (%)	Sample ID	Sample Date	Result (ug/L)	RPD (%)				
BAT-2S	08/05/1999	1,112,500	4.61	PA-4S	05/15/2000	<5.0					
BAT-2S DUP		1,165,000		PA-4S DUP		<5.0	0.00				
BAT-5I	08/05/1999	867,500	3.40	BAT-3S	05/15/2000	630,000					
BAT-5I DUP		897,500		BAT-3S DUP		600,000	4.88				
BAT-2S	08/09/1999	1,100,000	0.00	BAT-5D	05/18/2000	52,000					
BAT-2S DUP		1,100,000		BAT-5D DUP		49,000	5.94				
BAT-5I	08/09/1999	960,000	23.26	PA-3S	05/18/2000	<5.0					
BAT-5I DUP		760,000		PA-3S DUP		<5.0	0.00				
				PA-1I	05/19/2000	<2,000					
				PA-1I DUP		<2,000	0.00				

**Table G-6. Results and Precision of the Field Duplicate Samples Collected During the Oxidation Demonstration Groundwater Sampling**  
**Oxidation Treatment Plot Field Duplicate Groundwater Samples**  
**QA/QC Target Level < 30.0 %**

Demonstration						Groundwater Sampling					
Sample ID	Sample Date	Result (ug/L)	RPD (%)	Sample ID	Sample Date	Result (ug/L)	RPD (%)				
PA-3I	09/28/1999	1,150,000	0.87	BAT-5D	11/16/1999	730,000					
PA-3I DUP		1,160,000		BAT-5D DUP		725,000	0.69				
PA-8D	09/29/1999	625,000	11.86	BAT-2I	01/12/2000	50,000					
PA-8D DUP		555,000		BAT-2I DUP		48,200	3.67				
PA-8S	10/20/1999	115,000	1.75	PA-3D	01/12/2000	650,000					
PA-8S DUP		113,000		PA-3D DUP		680,000	4.51				
BAT-2I	10/25/1999	68,800	12.51	BAT-5D	04/12/2000	870,000					
BAT-2I DUP		60,700		BAT-5D DUP		910,000	4.49				
MP-2B	10/26/1999	290	9.01	PA-9S	04/13/2000	220,000					
MP-2B DUP		265		PA-9S DUP		230,000	4.44				

**Table G-7. Rinsate Blank Results for Groundwater Samples Collected for the Oxidation Pre-and Post-Demonstration Groundwater Sampling**

Oxidation Pre-Demonstration Groundwater QA/QC Samples			Total Number of Samples Collected = 107 (Pre-) 80 (Post-)
QA/QC Target Level < 3.0 ug/L			Total Number of Rinsate Blank Samples Analyzed = 11
Pre-Demonstration Rinsate Blanks			Post-Demonstration Rinsate Blanks
Analysis Date	TCE Concentration (ug/L)	Comments	
08/05/1999	3,236.0	Before switching to disposal tubing.	05/16/2000 0.25 Met QA/QC Target Criteria
08/05/1999	227.0	Before switching to disposal tubing.	05/17/2000 0.33 Met QA/QC Target Criteria
08/07/1999	58.3	Before switching to disposal tubing.	05/19/2000 1.1 Met QA/QC Target Criteria
08/10/1999	2,980.0	Before switching to disposal tubing.	05/20/2000 11.0 <sup>a)</sup> Sampling procedure for this set repeated.
08/12/1999	140.0	Before switching to disposal tubing.	
08/12/1999	31.3	Before switching to disposal tubing.	
08/12/1999	339.0	Before switching to disposal tubing.	

a) Samples in this set included PA-12D, PA-11S, I, D. PA-11I and PA-11D were collected after, but the field blank sample was less than 10% of the concentration results in these two samples.

**Table G-8. Rinsate Blank Results for Groundwater Samples Collected for the Oxidation Demonstration Groundwater Sampling**

Oxidation Demonstration Groundwater QA/QC Samples			Total Number of Samples Collected = 154
QA/QC Target Level < 3.0 ug/L			Total Number of Rinsate Blank Samples Analyzed = 22
Demonstration			Demonstration
Analysis Date	TCE Concentration (ug/L)	Comments	
09/27/1999	174.0	Before switching to disposal tubing.	10/22/1999 <2.0 Met QA/QC Target Criteria
09/27/1999	170.0	Before switching to disposal tubing.	10/26/1999 <2.0 Met QA/QC Target Criteria
09/27/1999	233.0	Before switching to disposal tubing.	10/26/1999 <2.0 Met QA/QC Target Criteria
09/28/1999	79.5	Before switching to disposal tubing.	11/16/1999 <2.0 Met QA/QC Target Criteria
09/28/1999	2,740.0	Before switching to disposal tubing.	01/11/2000 <2.0 Met QA/QC Target Criteria
09/28/1999	2,430.0	Before switching to disposal tubing.	01/12/2000 <2.0 Met QA/QC Target Criteria
09/30/1999	46.3	Before switching to disposal tubing.	01/13/2000 <3.0 Met QA/QC Target Criteria
09/28/1999	43.8	Before switching to disposal tubing.	01/14/2000 <2.0 Met QA/QC Target Criteria
09/28/1999	29.2	Before switching to disposal tubing.	04/11/2000 <1.0 Met QA/QC Target Criteria
10/06/1999	<2.0	Met QA/QC Target Criteria	04/12/2000 <1.0 Met QA/QC Target Criteria
10/07/1999	<2.0	Met QA/QC Target Criteria	04/13/2000 <1.0 Met QA/QC Target Criteria

**Table G-9. Results of the Trip Blank Samples Analyzed During the Oxidation Demonstration Soil and Groundwater Sampling**

**Total Number of Samples Collected = 665 (Soil) 496 (Groundwater) <sup>(a)</sup>**

**Total Number of Field Samples Analyzed = 14**

Oxidation Demonstration Trip Blanks						
Sample ID	Sample Date	Result (ug/L)	Comments	Sample ID	Sample Date	Result (ug/L)
Trip Blank-1	08/03/1999	<1.0	Met QA/QC target criteria.	Trip Blank-9	05/22/2000	<5.0
Trip Blank-2	01/05/2000	<1.0	Met QA/QC target criteria.	Trip Blank-10	05/23/2000	<5.0
Trip Blank-3	04/13/2000	<1.0	Met QA/QC target criteria.	Trip Blank-11	05/24/2000	<5.0
Trip Blank-4	04/13/2000	<1.0	Met QA/QC target criteria.	Trip Blank-12	05/25/2000	<5.0
Trip Blank-5	04/13/2000	<1.0	Met QA/QC target criteria.	Trip Blank-13	05/26/2000	<5.0
Trip Blank-6	05/09/2000	<1.0	Met QA/QC target criteria.	Trip Blank-14	06/01/2000	<5.0
Trip Blank-7	05/11/2000	<2.0	Met QA/QC target criteria.	Trip Blank-15	06/01/2000	<5.0
Trip Blank-8	05/19/2000	<5.0	Met QA/QC target criteria.	Trip Blank-16	06/02/2000	<5.0

(a) Groundwater samples that were analyzed by the on site mobile laboratory were not delivered with a trip blank sample for analysis.

Start of lab QA/QC

**Table G-10. Spike Recovery and Precision Values for Matrix Spike Samples Analyzed During the Oxidation Pre-Demonstration Soil Sampling**

Oxidation Treatment Plot MS/MSD Samples		Total Number of Soil Samples Collected = 308	
QA/QC Target Level Recovery % = 70 - 130 %		Total Number of MS/MSD Samples Analyzed = 12	
QA/QC Target Level < 30.0 %			

Pre-Demonstration					
Sample Date	TCE Recovery (%)	RPD (%)	Sample Date	TCE Recovery (%)	RPD (%)
06/28/1999	113	1.5	07/07/1999	118	1.5
	115			116	
06/30/1999	123	0.03	07/09/1999	112	0.4
	123			112	
07/02/1999	91	0.26	07/09/1999	106	0.19
	92			106	
07/02/1999	118	3.6	07/13/1999	119	0.02
	114			119	
07/05/1999	100	14.0	07/16/1999	117	2.8
	82			114	
07/06/1999	104	5.2	07/22/1999	111	0.32
	110			111	

**Table G-11. Spike Recovery and Precision Values for Matrix Spike Samples Analyzed During the Oxidation Post-Demonstration Soil Sampling**

Oxidation Treatment Plot MS/MSD Samples		Total Number of Soil Samples Collected = 357	
QA/QC Target Level Recovery % = 70 - 130 %		Total Number of MS/MSD Samples Analyzed = 21	
QA/QC Target Level < 30.0 %			
		Post-Demonstration	
Sample Date	TCE Recovery (%)	RPD (%)	TCE Recovery (%)
05/18/2000	96 97	0.27	05/24/2000 99
05/18/2000	96 98	1.80	05/24/2000 100
05/18/2000	102	11.00	05/24/2000 100
05/19/2000	91	4.40	05/25/2000 106
05/19/2000	87	4.40	05/25/2000 101
05/20/2000	94	1.80	05/26/2000 94
05/20/2000	91	1.80	05/26/2000 100
05/20/2000	93		3.80
05/20/2000	100	0.56	05/31/2000 88
05/20/2000	100		05/31/2000 104
05/22/2000	88	1.80	05/31/2000 104
05/22/2000	90		05/31/2000 144 <sup>(a)</sup>
05/22/2000	107	1.80	05/31/2000 127
05/22/2000	105		05/31/2000 81
05/22/2000	107		05/31/2000 111
05/22/2000	108	0.33	06/01/2000 53 <sup>(a)</sup>
05/23/2000	88	2.60	06/01/2000 73
05/23/2000	82		06/01/2000 179 <sup>(a)</sup>
05/23/2000	77	0.18	06/01/2000 129
05/23/2000	76		06/01/2000 12.00

(a) Samples had high RPD values due to the effect of low (or below detect) concentrations of TCE drastically affected the RPD calculation.

**Table G-12. Spike Recovery Values for Soil Laboratory Control Spike Samples Collected for the Oxidation Pre-Demonstration**

Oxidation Treatment Plot LCS/LCSD Samples		Total Number of Soil Samples Collected = 308	
QA/QC Target Level Recovery % = 70 – 130 %		Total Number of LCS/LCSD Samples Analyzed = 22	
QA/QC Target Level < 30.0 %			
<b>Pre-Demonstration</b>			
Sample Date	TCE Recovery (%)	RPD (%)	Sample Date
06/28/1999	110	4.6	07/06/1999
	105		
	121	2.4	
	124		
06/30/1999	109	0.46	07/06/1999
	108		
	122	1.9	
	120		
07/01/1999	94	1.6	07/08/1999
	95		
	122		
	104		
07/02/1999	92	0.91	07/09/1999
	93		
	107	2.5	
	110		
07/02/1999	118	3.6	07/12/1999
	114		
	92	3.9	07/14/1999
	96		
07/04/1999	110	0.88	07/21/1999
	109		
	117	0.76	07/24/1999
07/06/1999	118		

Sample Date	TCE Recovery (%)	RPD (%)	Sample Date	TCE Recovery (%)	RPD (%)
06/28/1999	110	4.6	07/06/1999	91	2.0
	105			93	
	121	2.4		118	
	124			117	0.48
06/30/1999	109	0.46	07/07/1999	112	0.73
	108			113	
	122	1.9		104	0.36
	120			104	
07/01/1999	94	1.6	07/08/1999	89	5.0
	95			94	
	122			104	
	104			104	
07/02/1999	92	0.91	07/09/1999	110	1.5
	93			111	
	107	2.5		116	
	110			111	
07/02/1999	118	3.6	07/12/1999	116	4.9
	114			116	
	92	3.9	07/14/1999	110	0.6
	96			110	
07/04/1999	110	0.88	07/21/1999	110	2.4
	109			112	
	117	0.76	07/24/1999	117	0.6
07/06/1999	118			117	

**Table G-13. Spike Recovery Values for Soil Laboratory Control Spike Samples Collected for the Oxidation Post-Demonstration**

Oxidation Treatment Plot LCS/LCSD Samples			Total Number of Soil Samples Collected = 357		
QA/QC Target Level Recovery % = 70 - 130 %			Total Number of LCS/LCSD Samples Analyzed = 30		
QA/QC Target Level < 30.0 %					
Post-Demonstration					
Sample Date	TCE Recovery (%)	RPD (%)	Sample Date	TCE Recovery (%)	RPD (%)
05/25/2000	96	0.27	05/31/2000	76	18.0
	97			118	
05/25/2000	96	1.8	05/31/2000	88	2.6
	98			82	
05/25/2000	102	11.0	05/31/2000	77	0.18
	91			76	
05/26/2000	100	0.56	05/31/2000	123	2.7
	100			132 <sup>(a)</sup>	
05/26/2000	87	4.4	05/31/2000	93	6.8
	94			99	
05/28/2000	88	1.8	06/01/2000	93	6.8
	90			99	
05/28/2000	106	4.9	06/02/2000	134 <sup>(a)</sup>	5.4
	101			106	
05/28/2000	100	1.4	06/03/2000	100	0.12
	101			100	
05/29/2000	91	1.8	06/05/2000	88	3.8
	93			88	
05/29/2000	88	1.8	06/06/2000	104	0.23
	90			104	
05/29/2000	85	6.1	06/06/2000	101	3.0
	90			94	
05/30/2000	107	1.8	06/07/2000	81	5.0
	105			111	
05/30/2000	112	0.17	06/07/2000	144 <sup>(a)</sup>	2.6
	111			127	
05/31/2000	107	0.33	06/09/2000	96	1.2
	108			97	

(a) Outside the targeted range, but at measurable levels, given the possible matrix interference from the potassium permanganate injection.

**Table G-14. Method Blank Samples Analyzed During the Oxidation Pre-Demonstration Soil Sampling**

Oxidation Pre-Demonstration Soil QA/QC Samples  
QA/QC Target Level < 1.0 mg/kg

Pre-Demonstration Method Blanks					
Analysis Date	TCE Concentration (mg/kg)	Comments	Analysis Date	TCE Concentration (mg/kg)	Comments
06/28/1999	<0.250	Met QA/QC Target Criteria	07/06/1999	<0.250	Met QA/QC Target Criteria
06/28/1999	<0.250	Met QA/QC Target Criteria	07/06/1999	<0.250	Met QA/QC Target Criteria
06/30/1999	<0.250	Met QA/QC Target Criteria	07/06/1999	<0.250	Met QA/QC Target Criteria
06/30/1999	<0.250	Met QA/QC Target Criteria	07/06/1999	<0.250	Met QA/QC Target Criteria
06/30/1999	<0.250	Met QA/QC Target Criteria	07/07/1999	<0.250	Met QA/QC Target Criteria
06/30/1999	<0.250	Met QA/QC Target Criteria	07/07/1999	<0.250	Met QA/QC Target Criteria
06/30/1999	<0.250	Met QA/QC Target Criteria	07/08/1999	<0.250	Met QA/QC Target Criteria
07/01/1999	<0.250	Met QA/QC Target Criteria	07/09/1999	<0.250	Met QA/QC Target Criteria
07/02/1999	<0.250	Met QA/QC Target Criteria	07/09/1999	<0.250	Met QA/QC Target Criteria
07/02/1999	<0.250	Met QA/QC Target Criteria	07/09/1999	<0.250	Met QA/QC Target Criteria
07/02/1999	<0.250	Met QA/QC Target Criteria	07/09/1999	<0.250	Met QA/QC Target Criteria
07/02/1999	<0.250	Met QA/QC Target Criteria	07/09/1999	<0.250	Met QA/QC Target Criteria
07/02/1999	<0.250	Met QA/QC Target Criteria	07/12/1999	<0.250	Met QA/QC Target Criteria
07/02/1999	<0.250	Met QA/QC Target Criteria	07/13/1999	<0.250	Met QA/QC Target Criteria
07/03/1999	<0.250	Met QA/QC Target Criteria	07/13/1999	<0.250	Met QA/QC Target Criteria
07/04/1999	<0.250	Met QA/QC Target Criteria	07/14/1999	<0.250	Met QA/QC Target Criteria
07/05/1999	<0.250	Met QA/QC Target Criteria	07/21/1999	<0.250	Met QA/QC Target Criteria
07/06/1999	<0.250	Met QA/QC Target Criteria	07/22/1999	<0.250	Met QA/QC Target Criteria
07/06/1999	<0.250	Met QA/QC Target Criteria	07/23/1999	<0.250	Met QA/QC Target Criteria
07/06/1999	<0.250	Met QA/QC Target Criteria	07/24/1999	<0.250	Met QA/QC Target Criteria
07/01/1999	<0.250	Met QA/QC Target Criteria	07/09/1999	<0.250	Met QA/QC Target Criteria
07/01/1999	<0.250	Met QA/QC Target Criteria	07/09/1999	<0.250	Met QA/QC Target Criteria
07/15/1999	<0.250	Met QA/QC Target Criteria	07/09/1999	<0.250	Met QA/QC Target Criteria
07/15/1999	<0.250	Met QA/QC Target Criteria	07/12/1999	<0.250	Met QA/QC Target Criteria

**Table G-15. Method Blank Samples Analyzed During the Oxidation Post-Demonstration Soil Sampling**  
**Oxidation Pre-Demonstration Soil QA/QC Samples**  
**QA/QC Target Level < 1.0 mg/kg**

Post-Demonstration Method Blanks					
Analysis Date	TCE Concentration (mg/kg)	Comments	Analysis Date	TCE Concentration (mg/kg)	Comments
05/25/2000	<0.250	Met QA/QC Target Criteria	05/31/2000	<0.250	Met QA/QC Target Criteria
05/25/2000	<0.250	Met QA/QC Target Criteria	06/01/2000	<0.250	Met QA/QC Target Criteria
05/25/2000	<0.250	Met QA/QC Target Criteria	05/19/2000	<0.250	Met QA/QC Target Criteria
05/26/2000	<0.250	Met QA/QC Target Criteria	06/01/2000	<0.250	Met QA/QC Target Criteria
05/27/2000	<0.250	Met QA/QC Target Criteria	06/01/2000	<0.250	Met QA/QC Target Criteria
05/27/2000	<0.250	Met QA/QC Target Criteria	06/02/2000	<0.250	Met QA/QC Target Criteria
05/28/2000	<0.250	Met QA/QC Target Criteria	06/02/2000	<0.250	Met QA/QC Target Criteria
05/28/2000	<0.250	Met QA/QC Target Criteria	06/02/2000	<0.250	Met QA/QC Target Criteria
05/28/2000	<0.250	Met QA/QC Target Criteria	06/03/2000	<0.250	Met QA/QC Target Criteria
05/28/2000	<0.250	Met QA/QC Target Criteria	06/05/2000	<0.250	Met QA/QC Target Criteria
05/29/2000	<0.250	Met QA/QC Target Criteria	06/06/2000	<0.250	Met QA/QC Target Criteria
05/29/2000	<0.250	Met QA/QC Target Criteria	06/07/2000	<0.250	Met QA/QC Target Criteria
05/30/2000	<0.250	Met QA/QC Target Criteria	06/07/2000	<0.250	Met QA/QC Target Criteria
05/30/2000	<0.250	Met QA/QC Target Criteria	06/07/2000	<0.250	Met QA/QC Target Criteria
05/30/2000	<0.250	Met QA/QC Target Criteria	06/07/2000	<0.250	Met QA/QC Target Criteria
05/30/2000	<0.250	Met QA/QC Target Criteria	06/07/2000	<0.250	Met QA/QC Target Criteria
05/30/2000	<0.250	Met QA/QC Target Criteria	06/07/2000	<0.250	Met QA/QC Target Criteria
05/31/2000	<0.250	Met QA/QC Target Criteria	06/08/2000	<0.250	Met QA/QC Target Criteria
05/31/2000	<0.250	Met QA/QC Target Criteria	06/09/2000	<0.250	Met QA/QC Target Criteria
05/31/2000	<0.250	Met QA/QC Target Criteria	06/01/2000	<0.250	Met QA/QC Target Criteria

**Table G-16. Spike Recovery and Precision Values for Matrix Spike Samples Analyzed During the Oxidation Demonstration Groundwater Sampling**

Oxidation Treatment Plot Groundwater QA/QC

QA/QC Target Level Recovery % = 70 – 130 %

QA/QC Target Level RPD < 30.0 %

**Oxidation Demonstration Matrix Spike Samples**

Sample ID	Sample Date	TCE Recovery (%)	RPD (%)	Sample ID	Sample Date	TCE Recovery (%)	RPD (%)
BAT-2S MS	08/03/1999	104	0.11	MP-2C MS	10/26/1999	109	0.4
BAT-2S MSD		103		MP-2C MSD		109	
BAT-5I MS	08/03/1999	51 <sup>(a)</sup>	5.6	ML-2 MS	01/14/2000	181 <sup>(a)</sup>	6.63
BAT-5I MSD		27 <sup>(a)</sup>		ML-2 MSD		202 <sup>(a)</sup>	
PA-7D MS	08/07/1999	92.0	0.6	PA-3D DUP MS	01/15/2000	130	0.874
PA-7D MSD		96.0		PA-3D DUP MSD		126	
MP-3A MS	09/30/1999	89	4.3	PA-1D MS	01/16/2000	94	3.56
MP-3A MSD		82		PA-1D MSD		98	
ML-2 MS	10/25/1999	116	0.9	PA-8S MS	06/15/2000	78	
ML-2 MSD		115		PA-8S MSD		88	12.0

(a) TCE recovery was affected by interference from excess potassium permanganate in these groundwater samples.

**Table G-17. Spike Recovery and Precision Values for Laboratory Control Spike Samples Analyzed During the Pre- and Post-Demonstration Groundwater Sampling**

Oxidation Treatment Plot Groundwater QA/QC				Total Number of Samples Collected = 107 (Pre-) 80 (Post-)			
QA/QC Target Level Recovery % = 70 - 130 %				Total Number of Matrix Spike Samples Analyzed = 18			
QA/QC Target Level RPD < 30.0 %							
Pre-Demonstration LCS/LCSD Samples				Post-Demonstration LCS/LCSD Samples			
Sample ID	Sample Date	TCE Recovery (%)	RPD (%)	Sample ID	Sample Date	TCE Recovery (%)	RPD (%)
LCS-990805	08/05/1999	115	5.9	DD6K8102-LCS	05/15/2000	91	2.6
LCSD-990805		122		DD6K8103-LCSD		93	
LCS-990806	08/06/1999	107	3.1	DD7IQ102-LCS	05/16/2000	93	3.6
LCSD-990806		111		DD7IQ103-LCSD		97	
LCS-990807	08/07/1999	113	0.4	DDC22102-LCS	05/18/2000	94	
LCSD-990807		113		DDC22103-LCSD		93	
LCS-990809	08/09/1999	109	2.0	DDDEQ102-LCS	05/18/2000	96	1.9
LCSD-990809		106		DDDEQ103-LCSD		97	
LCS-990810	08/10/1999	111	2.5	DDF78102-LCS	05/19/2000	84	2.9
LCSD-990810		109		DDF78103-LCSD		87	
LCS-990811	08/11/1999	112	3.8	DDG8R102-LCS	05/20/2000	100	4.2
LCSD-990811		108		DDG8R103-LCSD		95	
LCS-990812	08/12/1999	106	0.6	DDH5F102-LCS	05/21/2000	97	
LCSD-990812		105		DDH5F103-LCSD		92	
LCS-990813	08/13/1999	98	4.0	DDH76102-LCS	05/22/2000	90	4.9
LCSD-990813		102		DDH76103-LCSD		91	
				DF2FM102-LCS	06/20/2000	84	1.1
				DF2FM103-LCSD		94	
				DF4F5102-LCS	06/21/2000	89	11.0
				DF4F5103-LCSD		88	0.88

**Table G-18. Spike Recovery and Precision Values for Laboratory Control Spike Samples Analyzed During the Oxidation Demonstration Groundwater Sampling**

Oxidation Treatment Plot Groundwater QA/QC QA/QC Target Level Recovery % = 70 - 130 % QA/QC Target Level RPD < 30.0 %				Demonstration LCS/LCSD Spike Samples			
Sample ID	Sample Date	TCE Recovery (%)	RPD (%)	Sample ID	Sample Date	TCE Recovery (%)	RPD (%)
LCS-990927	09/27/1999	95	12.1	LCS-991025	10/25/1999	113	0.9
LCSD-990927		107		LCSD-991025		112	
LCS-990928	09/28/1999	113	5.1	LCS-991026	10/26/1999	112	4.6
LCSD-990928		107		LCSD-991026		107	
LCS-990929	09/29/1999	107	4.2	LCS-991118	11/18/1999	109	17.6
LCSD-990929		111		LCSD-991118		91	
LCS-991018	10/18/1999	114	1.4	LCS-00113	01/13/2000	101	-
LCSD-991018		115		LCSD-00113		-	
LCS-991019	10/19/1999	119	6.2	LCS-00114	01/14/2000	106	-
LCSD-991019		112		LCSD-00114		-	
LCS-991020	10/20/1999	109	9.8	LCS-00115	01/15/2000	113	1.16
LCSD-991020		99		LCSD-00115		103	
LCS-991021	10/21/1999	111	5.3	LCS-00116	01/16/2000	104	1.94
LCSD-991021		117		LCSD-00116		102	
LCS-991022	10/22/1999	108	3.3				
LCSD-991022		112					

Total Number of Samples Collected = 309  
Total Number of Matrix Spike Samples Analyzed = 15

**Table G-19. Method Blank Samples Analyzed During the Oxidation Pre-Demonstration Groundwater Sampling**

Oxidation Pre- and Post-Demo Groundwater QA/QC Samples			Total Number of Samples Collected = 107 (Pre-) 80 (Post-)	
QA/QC Target Level < 3.0 ug/L			Total Number of Method Blank Samples Analyzed = 18	
Pre-Demonstration Method Blanks			Post-Demonstration Method Blanks	
Analysis Date	TCE Concentration (ug/L)	Comments	Analysis Date	
			TCE Concentration (ug/L)	
08/05/1999	<2.0	Met QA/QC Target Criteria	08/09/1999	<1.0
08/06/1999	<2.0	Met QA/QC Target Criteria	05/15/2000	<1.0
08/07/1999	<2.0	Met QA/QC Target Criteria	05/16/2000	<1.0
08/08/1999	<2.0	Met QA/QC Target Criteria	05/18/2000	<1.0
08/09/1999	<2.0	Met QA/QC Target Criteria	05/18/2000	<1.0
08/10/1999	<2.0	Met QA/QC Target Criteria	05/19/2000	<1.0
08/11/1999	<2.0	Met QA/QC Target Criteria	05/20/2000	<1.0
08/12/1999	<2.0	Met QA/QC Target Criteria	05/21/2000	<1.0
08/09/1999	<1.0	Met QA/QC Target Criteria	05/22/2000	<1.0

**Table G-20. Method Blank Samples Analyzed During the Oxidation Demonstration Groundwater Sampling**

Oxidation Demonstration Groundwater QA/QC Samples			Total Number of Samples Collected = 309	
QA/QC Target Level < 3.0 ug/L			Total Number of Method Blank Samples Analyzed = 21	
Demonstration			Demonstration	
Analysis Date	TCE Concentration (ug/L)	Comments	Analysis Date	
			TCE Concentration (ug/L)	
09/27/1999	<2.0	Met QA/QC Target Criteria	11/16/1999	<2.0
09/28/1999	<2.0	Met QA/QC Target Criteria	01/13/2000	<2.0
09/29/1999	<2.0	Met QA/QC Target Criteria	01/14/2000	<2.0
09/30/1999	<2.0	Met QA/QC Target Criteria	01/15/2000	<2.0
10/06/1999	<2.0	Met QA/QC Target Criteria	01/16/2000	<2.0
10/07/1999	<2.0	Met QA/QC Target Criteria	01/17/2000	<2.0
10/20/1999	<2.0	Met QA/QC Target Criteria	04/11/2000	<1.0
10/21/1999	<2.0	Met QA/QC Target Criteria	04/13/2000	<1.0
10/22/1999	<2.0	Met QA/QC Target Criteria	04/18/2000	<1.0
10/25/1999	<2.0	Met QA/QC Target Criteria	04/21/2000	<1.0
10/26/1999	<2.0	Met QA/QC Target Criteria		

## **Appendix H. Economic Analysis Information**

Table H-1 to H-3. Pump-and-Treat System Costs  
Figure H-1. Pump-and-Treat Cost versus Time Chart

## Appendix H

### Economic Analysis Information

This appendix details the cost assessment for the application of the pump and treat (P&T) system for containment of a DNAPL source at Launch Complex 34, for a source zone that is the same size as the Oxidation Plot. Because the groundwater flow in this area is generally to the northeast, the DNAPL source could be contained by installing one or more extraction wells on the northeast side of the Oxidation Plot. The life cycle cost of a pump-and-treat system can be compared to the cost of DNAPL source removal using chemical oxidation, as described in Section 7 of the main report.

Experience at previous sites indicates that the most efficient long-term P&T system is one that is operated at the minimum rate necessary to contain a plume or source zone (Cherry et al., 1996). Table H-1 shows a preliminary size determination for the P&T system. The P&T system should be capable of capturing the groundwater flowing through a cross-section that is approximately 50 ft wide (width of Oxidation Plot) and 40 ft deep (thickness of surficial aquifer). Because capture with P&T systems is somewhat inefficient in that cleaner water from surrounding parts of the aquifer may also be drawn in, an additional safety factor of 100% was applied to ensure that any uncertainties in aquifer capture zone or DNAPL source characterization are accounted for. An extraction rate of 2 gallon per minute (gpm) is found to be sufficient to contain the source.

One advantage of low groundwater extraction rates is that the air effluent from stripping often does not have to be treated, as the rate of volatile organic compound (VOC) discharge to the ambient air is often within regulatory limits. The longer period of operation required (at a low withdrawal rate) is more than offset by higher efficiency (lower influx of clean water from outside the plume), lower initial capital investment (smaller treatment system), and lower annual operations and maintenance (O&M) requirements. Another advantage of a containment type P&T system is that, unlike source removal technologies, it does not require very extensive DNAPL zone characterization.

#### **H.1.1 Capital Investment for the P&T System**

The P&T system designed for this application consists of the components shown in Table H-2. Pneumatically driven pulse pumps, which are used in each well, are safer than electrical pumps in the presence of trichloroethylene (TCE) vapors in the wells. This type of pump can sustain low flowrates during continuous operation. Stainless steel and Teflon™ construction ensure compatibility with the high concentrations (up to 1,100 mg/L TCE) of dissolved solvent and any free-phase DNAPL that may be expected. Extraction wells are assumed to be 40 ft deep, 2 inches in diameter, and have stainless steel screens with polyvinyl chloride (PVC) risers.

The aboveground treatment system consists of a DNAPL separator and air stripper. Very little free-phase solvent is expected and the separator may be disconnected after the first year of operation, if desired. The air stripper used is a low-profile tray-type air stripper. As opposed to conventional packed towers, low-profile strippers have a smaller footprint, much smaller height, and can handle large air:water ratios (higher mass transfer rate of contaminants) without generating significant pressure losses. Because of their small size and easy installation, they are more often used in groundwater remediation. The capacity of the air stripper selected is much higher than 2 gpm, so that additional flow (or additional extraction wells) can be handled if required.

The high air:water ratio ensures that TCE (and other minor volatile components) are removed to the desired levels. The treated water effluent from the air stripper is discharged to the sewer. At the low groundwater extraction rate required, the resulting contaminant mass in the air effluent from the stripper is less than 2 lbs/day, and below a typical regulatory limit of 6 lbs/day. The air effluent can be discharged without further treatment.

The piping from the wells to the air stripper is run through a 1-ft-deep covered trench. The air stripper and other associated equipment are housed on a 20-ft-x-20-ft concrete pad, covered by a basic shelter. The base will provide a power drop (through a pole transformer) and a licensed electrician will be used for the power hookups. Meters and control valves are strategically placed to control water and air flow through the system.

The existing monitoring system at the site will have to be supplemented with seven long-screen (10-foot screen) monitoring wells. The objective of these wells is to ensure that the desired containment is being achieved.

#### **H.1.2 Annual Cost of the P&T System**

The annual costs of P&T are shown in Table H-3 and include annual operation and maintenance (O&M) and monitoring. Annual O&M costs include the labor, materials, energy, and waste disposal cost of operating the system and routine maintenance (including scheduled replacement of seals, gaskets, and O-rings). Routine monitoring of the stripper influent and effluent is done through ports on the feed and effluent lines on a monthly basis. Groundwater monitoring is conducted on a quarterly basis through seven monitoring wells. All water samples are analyzed for PCE and other chlorinated volatile organic compound (CVOC) by-products.

#### **H.1.3 Periodic Maintenance Cost**

In addition to the routine maintenance described above, periodic maintenance will be required, as shown in Table H-3, to replace worn-out equipment. Based on manufacturers' recommendations for the respective equipment, replacement is done once in 5 or 10 years. In general, all equipment involving moving parts is assumed will be replaced once every 5 years, whereas other equipment is changed every 10 years.

#### **H.1.4 Present Value (PV) Cost of P&T**

Because a P&T system is operated for the long term, a 30-year period of operation is assumed for estimating cost. Because capital investment, annual costs, and periodic maintenance costs occur at different points in time, a life cycle analysis or present value analysis is conducted to estimate the long-term cost of P&T in today's dollars. This life cycle analysis approach is recommended for long-term remediation applications by the guidance provided in the Federal Technologies Roundtable's *Guide to Documenting and Managing Cost and Performance Information for Remediation Projects* (United States Environmental Protection Agency [U.S. EPA], 1998). The PV cost can then be compared with the cost of faster (DNAPL source reduction) remedies.

$$PV_{P\&T \text{ costs}} = \frac{\Sigma \text{Annual Cost in Year } t}{(1 + r)^t} \quad \text{Equation (H-1)}$$

$$PV_{P\&T \text{ costs}} = \frac{\text{Capital Investment} + \text{Annual cost in Year 1} + \dots + \text{Annual cost in Year n}}{(1 + r)^1 + (1 + r)^n}$$

Equation (H-2)

Table 4 shows the PV calculation for P&T based on Equation 1. In Equation 1, each year's cost is divided by a discount factor that reflects the rate of return that is foregone by incurring the cost. As seen in Equation 2, at time  $t = 0$ , which is in the present, the cost incurred is the initial capital investment in equipment and labor to design, procure, and build the P&T system. Every year after that, a cost is incurred to operate and maintain the P&T system. A real rate of return (or discount rate),  $r$ , of 2.9% is used in the analysis as per recent U.S. EPA guidance on discount rates (U.S. EPA, 1999). The total PV cost of purchasing, installing, and operating a 1-gpm P&T source containment system for 30 years is estimated to be \$1,032,000 (rounded to the nearest thousand).

Long-term remediation costs are typically estimated for 30-year periods as mentioned above. Although the DNAPL source may persist for a much longer time, the contribution of costs incurred in later years to the PV cost of the P&T system is not very significant and the total 30-year cost is indicative of the total cost incurred for this application. This can be seen from the fact that in Years 28, 29, and 30, the differences in cumulative PV cost are not as significant as the difference in, say, Years 2, 3, and 4. The implication is that, due to the effect of discounting, costs that can be postponed to later years have a lower impact than costs that are incurred in the present.

As an illustration of a DNAPL source that may last much longer than the 30-year period of calculation, Figure H-1 shows a graphic representation of PV costs assuming that the same P&T system is operated for 100 years instead of 30 years. The PV cost curve flattens with each passing year. The total PV cost after 100 years is estimated at \$1,624,000.

**Table H-1. Pump & Treat (P&T) System Design Basis for Site 88 DNAPL Zone at Camp**

Item	Value	Units	Item	Value	Units
Width of DNAPL zone, w	50	ft	Hyd. conductivity, K	40	ft/d
Depth of DNAPL zone, d	40	ft	Hyd. gradient, I	0.0007	ft/ft
Crosssectional area of DNAPL zone, a	2000	sq ft	Porosity, n	0.3	
Capture zone required	187	cu ft/d	Gw velocity, v	0.093333	ft/d
Safety factor, 100%	2				
Required capture zone	373	cu ft/d	GPM =	1.9	gpm
Design pumping rate	2	gpm	Number of wells to achieve capture	1	
Pumping rate per well	2	gpm			
TCE conc. in water near DNAPL zone	100	mg/L	TCE allowed in discharge water	1	mg/L
Air stripper removal efficiency required	99.00%				
TCE in air effluent from stripper	2.4	lbs/day	TCE allowed in air effluent	6	lbs/day

**Table H-2. Capital Investment for a P&T System at Launch Complex 34, Cape Canaveral**

Item	Units	Unit Price	Cost	Basis
<b>Design/Procurement</b>				
Engineer	160	hrs	\$85	\$13,600
Drafter	80	hrs	\$40	\$3,200
Hydrologist	160	hrs	\$85	\$13,600
Contingency	1	ea	\$10,000	\$10,000 10% of total capital
TOTAL			\$30,400	
<b>Pumping system</b>				
Extraction wells	1	ea	\$5,000	\$5,000 2-inch, 40 ft deep, 30-foot SS screen; PVC; includes installation
Pulse pumps	1	ea	\$595	\$595 2.1 gpm max., 1.66"OD for 2-inch wells; handles solvent contact; pneumatic; with check valves
Controllers	1	ea	\$1,115	\$1,115 Solar powered or 110 V; with pilot valve
Air compressor	1	ea	\$645	\$645 100 psi (125 psi max), 4.3 cfm continuous duty, oil-less; 1 hp
Miscellaneous fittings	1	ea	\$5,000	\$5,000 Estimate
Tubing	150	ft	\$3	\$509 1/2-inch OD, chemical resistant; well to surface manifold
TOTAL			\$12,864	
<b>Treatment System</b>				
Piping	150	ft	\$3	\$509 chemical resistant
Trench	1	day	\$320	\$320 ground surface
DNAPL separator tank	1	ea	\$120	\$120 125 gal; high grade steel with epoxy lining; conical bottom with discharge
Air stripper feed pump	1	ea	\$460	\$460 0.5 hp; up to 15 gpm
Piping	50	ft	\$3	\$170 0.5 inch, chemical resistant; feed pump to stripper
Water flow meter	1	ea	\$160	\$160 Low flow; with read out
Low-profile air stripper with control panel	1	ea	\$9,400	\$9,400 1-25 gpm, 4 tray; SS shell and trays
Pressure gauge	1	ea	50	\$50 SS; 0-30 psi
Blower	1	ea	\$1,650	\$1,650 5 hp
Air flow meter	1	ea	\$175	\$175 Orifice type; 0-50 cfm
Stack	10	ft	\$2	\$20 2 inch, PVC, lead out of housing
Carbon	2	ea	\$1,000	\$2,000
Stripper sump pump	1	ea	\$130	\$130 To sewer
Misc. fittings, switches	1	ea	\$5,000	\$5,000 Estimate (sample ports, valves, etc.)
TOTAL			\$20,163	
<b>Site Preparation</b>				
Concrete pad	400	sq ft	\$3	\$1,200 20 ft x 20 ft with berm; for air stripper and associated equipment
Berm	80	ft	\$7	\$539
Power drop	1	ea	\$5,838	\$5,838 230 V, 50 Amps; pole transformer and licensed electrician
Monitoring wells	5	wells	\$2,149	\$10,745 Verify source containment; 2-inch PVC with SS screens
Sewer connection fee	1	ea	\$2,150	\$2,150
Sewer pipe	300	ft	\$10	\$3,102
Housing	1	ea	\$2,280	\$2,280 20 ft x 20 ft; shelter for air stripper and associated equipment
TOTAL			\$25,854	
<b>Installation/Start Up of Treatment System</b>				
Engineer	60	hrs	\$85	\$5,100 Labor
Technician	200	hrs	\$40	\$8,000 Labor
TOTAL			\$13,100	
<b>TOTAL CAPITAL INVESTMENT</b>			<b>\$102,381</b>	

Table H-2. Capital Investment for a P&T System at Launch Complex 34, Cape Canaveral (continued)

O&M Cost for P&T System					
Annual Operation & Maintenance					
Engineer	80	hrs	\$85	\$6,800	Oversight
Technician	500	hrs	\$40	\$20,000	Routine operation; annual cleaning of air stripper trays, routine replacement of parts; any waste disposal
Replacement materials	1	ea	\$2,000	\$2,000	Seals, o-rings, tubing, etc.
Electricity	52,560	kW-hrs	\$0.10	\$5,256	8 hp (~6 kW) over 1 year of operation
Sewer disposal fee	525,600	gal/yr	\$0.00152	\$799	
Carbon disposal	2		\$1,000	\$2,000	
Waste disposal	1	drum	\$80	\$200	30 gal drum; DNAPL, if any; haul to incinerator
TOTAL				\$37,055	
<b>Annual Monitoring</b>					
Air stripper influent	12	smpls	\$120	\$1,440	Verify air stripper loading; monthly
Air stripper effluent	14	smpls	\$120	\$1,680	Discharge quality confirmation; monthly; CVOC analysis; MS, MSD
Monitoring wells	34	smpls	\$120	\$4,080	5 wells; quarterly; MS, MSD
Sampling materials	1	ea	\$500	\$500	Miscellaneous
Technician	64	hrs	40	\$2,560	Quarterly monitoring labor (from wells) only; weekly monitoring (from sample ports) included in O&M cost
Engineer	40	hrs	85	\$3,400	Oversight; quarterly report
TOTAL				\$7,200	
<b>TOTAL ANNUAL COST</b>				<b>\$44,255</b>	
<b>Periodic Maintenance, Every 5 years</b>					
Pulse pumps	4	ea	\$595	\$2,380	As above
Air compressor	1	ea	\$645	\$645	As above
Air stripper feed pump	1	ea	\$460	\$460	As above
Blower	1	ea	\$1,650	\$1,650	As above
Stripper sump pump	1	ea	\$130	\$130	As above
Miscellaneous materials	1	ea	\$1,000	\$1,000	Estimate
Technician	40	hrs	\$40	\$1,600	Labor
TOTAL				<b>\$7,865</b>	
				<b>\$52,120</b>	
<b>Periodic Maintenance, Every 10 years</b>					
Air stripper	1	ea	\$9,400	\$9,400	As above
Water flow meters	1	ea	160	\$160	As above
Air flow meter	1	ea	175	\$175	As above
Technician	40	hrs	\$40	\$1,600	Labor
Miscellaneous materials	1	ea	\$1,000	\$1,000	Estimate
TOTAL				<b>\$12,335</b>	
<b>TOTAL PERIODIC MAINTENANCE COSTS</b>				<b>\$64,455</b>	

**Table H-3. Present Value of P&T System Costs for 30 years of operation**

Year	P&T		Cumulative PV of Annual Cost
	Annual Cost *	PV of Annual Cost	
0	\$102,381	\$102,381	\$102,381
1	\$44,255	\$43,008	\$145,389
2	\$44,255	\$41,796	\$187,184
3	\$44,255	\$40,618	\$227,802
4	\$44,255	\$39,473	\$267,275
5	<b>\$52,120</b>	\$45,178	\$312,453
6	\$44,255	\$37,280	\$349,733
7	\$44,255	\$36,229	\$385,962
8	\$44,255	\$35,208	\$421,170
9	\$44,255	\$34,216	\$455,385
10	<b>\$64,455</b>	\$48,429	\$503,814
11	\$44,255	\$32,314	\$536,128
12	\$44,255	\$31,403	\$567,532
13	\$44,255	\$30,518	\$598,050
14	\$44,255	\$29,658	\$627,708
15	<b>\$52,120</b>	\$33,945	\$661,653
16	\$44,255	\$28,010	\$689,663
17	\$44,255	\$27,221	\$716,884
18	\$44,255	\$26,454	\$743,338
19	\$44,255	\$25,708	\$769,046
20	<b>\$64,455</b>	\$36,387	\$805,433
21	\$44,255	\$24,279	\$829,713
22	\$44,255	\$23,595	\$853,308
23	\$44,255	\$22,930	\$876,238
24	\$44,255	\$22,284	\$898,522
25	<b>\$52,120</b>	\$25,505	\$924,027
26	\$44,255	\$21,046	\$945,073
27	\$44,255	\$20,453	\$965,525
28	\$44,255	\$19,876	\$985,401
29	\$44,255	\$19,316	\$1,004,717
30	<b>\$64,455</b>	\$27,340	\$1,032,057

\* Annual cost in Year zero is equal to the capital investment.

Annual cost in other years is annual O&M cost plus annual monitoring cost

Annual costs in Years 10, 20, and 30 include annual

O&M, annual monitoring, and periodic maintenance

Figure H-1. P&T System Costs - 100 years

